KU LEUVEN

ARENBERG DOCTORAL SCHOOL
Faculty of Engineering Science

Unfolding data

Software and design approaches to support casual exploration of tempo-spatial data on interactive tabletops.

Till Nagel

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Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Engineering

January 2015

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January 2015

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ISBN 978-94-6018-949-4

D/2015/7515/5

Abstract

In recent years, increasingly large and complex data sets about our environment are generated by a vast system of sensors and devices. With the widespread dissemination of online maps, location based services, and mobile phones a large laymen audience is accustomed to using geo-spatial data in everyday life. While geovisualization have been used to make these accessible and to enable interactive exploration of tempospatial data, they are often aimed only at experts visually analyzing the data. There is the need for simpler, less complex geovisualizations, in order to engage non-experts to understand data and gain insights.

The general research objective of this dissertation is to facilitate exploring and understanding geospatial patterns, relationships, and trends for wider audience groups by designing comprehensible and easy-to-use interactive visualization systems for time-varying geo-referenced data. The general research question is how to design interactive geovisualization systems in such ways as to casually explore the visualized data, and ultimately gain insights into the presented domain.

Within our research, we designed and evaluated three case studies from different domains. With every case study we investigated its domain while following the shared main goal of enabling a casual exploration of geo-referenced data on a large interactive screen displayed in semi-public space. All three case studies offered visualizations of information relevant to people in both everyday work and non-work situations. This ranged from classic geo-spatial data such as information on buildings and places (Venice Unfolding), to geo-referenced social network data (Muse), to mobility data based both on authoritative data sources, as well as sensors and smart phones (Touching Transport). We designed fully functional interactive visualization systems for multitouch tabletops, and exhibited them in different venues. The developed prototypes themselves also act as artifacts which encapsulate our design decisions, and thus embody parts of our research results.

Prompted by the recurring issue of visualizing relations we created Sankey Arcs, a novel technique to visualize weighted relations, which also acted as an example for identifying a shared problem in case studies with similar characteristics, and designing a solution for it. Based on design objectives of the case studies, and the recurring task of constructing interactive geovisualizations, we developed the software library Unfolding Maps. We show that our software library supports a diverse set of users, and eases developing visualizations of geo-referenced data. We conclude with a critical reflection of our research approach, and a discussion of future perspectives in regards to follow-up work.

With our case studies we provided innovative solutions to our research questions by bringing together computer science with design in order to create geovisualizations on interactive tabletops for casual users. In the intersecting research fields lie visualization and interaction challenges, and new ways of developing and evaluating such systems. With the work discussed in this thesis we hope to motivate and further enable a new design space for casual exploration of geovisualizations.

Beknopte samenvatting

In de afgelopen jaren hebben sensor-gebaseerde technologieën en systemen steeds vaker grote en complexe datasets over onze omgeving gegenereerd. Met de grootschalige verspreiding van online kaarten, locatie-gebaseerde diensten en mobiele telefoons, is het grote algemene publiek gewend geraakt aan het dagelijkse gebruik van geo-ruimtelijke data. Hoewel geovisualisatie veelal wordt toegepast om deze data toegankelijk te maken en te zorgen voor de interactieve verkenning van tijd-ruimtelijke data, wordt dit vaak alleen gericht op experts die de data visueel wensen te analyseren. Er is dus een behoefte aan eenvoudigere, minder complexe geovisualisaties, waarmee niet-experts ook data kunnen begrijpen en inzicht verkrijgen.

Het algemene onderzoeksdoel van deze thesis is het faciliteren van het ontdekken en begrijpen van geo-ruimtelijke patronen, relaties en trends voor een breder publiek, aan de hand van uitgebreide doch gemakkelijk toepasbare interactieve visualisatiesystemen. De algemene onderzoeksvraag is hoe zulke interactieve geovisualisatiesystemen op zo een manier gebruikt kunnen worden, dat ze de mogelijkheid bieden voor het informeel verkennen van gevisualiseerde data om inzicht te verkrijgen in het gepresenteerde domein.

Binnen ons onderzoek hebben we drie case studies met betrekking tot verschillende domeinen opgezet en geëvalueerd. In elke case study hebben we het domein onderzocht, met als focus de verkenning van geografische referentiedata op een groot, interactief scherm, weergegeven in een semi-openbare ruimte. Alle case studies boden visualisaties aan van informatie die relevant waren voor mensen in zowel dagelijkse werksituaties als niet-werkgerelateerde situaties. De onderwerpen reikten van klassieke geo-ruimtelijke data, zoals informatie over gebouwen en plaatsen (Venice Unfolding), over geografische referenten sociaal netwerk-data (Muse), tot mobiliteitsdata, gebaseerd op zowel gezaghebbende databronnen en sensoren en smartphones (Touching Transport). We ontwierpen hiervoor volledig functionele interactieve visualisatiesystemen voor multitouch tabletops en stelden ze ten toon op verschillende locaties. De ontwikkelde

prototypen fungeerden ook als artefacten die onze ontwerpbeslissingen weergaven en als zodanig ook zelf deel werden van onze onderzoeksresultaten.

Naar aanleiding van het herhaalde gebruik van het visualiseren van complexe relaties hebben we Sankey Arcs ontwikkeld, een nieuwe techniek om gewogen relaties, die ook fungeren als voorbeeld voor het identificeren van een gedeeld probleem in case studies met gelijksoortige kenmerken, te visualiseren en hier een oplossing voor te ontwerpen. Op basis van de ontwerpdoelen van de case studies en de ervaring van het ontwikkelen van interactieve geovisualisaties hebben we de softwarebibliotheek genaamd Unfolding Maps ontwikkeld. We demonstreren dat onze softwarebibliotheek een brede set gebruikers ondersteunt en het ontwikkelen van unieke visualisaties op basis van geografische referentiedata makkelijker maakt. We sluiten af met een kritische reflectie op onze onderzoeksbenadering en een bespreking van toekomstige doelen met betrekking tot toekomstig werk.

Met onze case studies hebben we innovatieve antwoorden geboden op onze onderzoeksvragen, door computerwetenschappen samen te brengen met het ontwerpen, om zo geovisualisaties op interactieve tabletops te kunnen tonen voor gewone gebruikers. In de aanverwante onderzoeksvelden bevinden zich de uitdagingen op het gebied van visualisatie en interactie, nieuwe manieren om dergelijke systemen te ontwikkelen en te evalueren, als ook een nieuwe ontwerpruimte voor een informele verkenning van geovisualisaties te ontdekken. Het werk dat in deze thesis besproken wordt, richt zich op de eerste twee uitdagingen, om de derde vervolgens beter mogelijk te maken en te motiveren.

Acknowledgement

First, I would like to express my sincere gratitude to my promoter Erik Duval for his inspiration and guidance over the last years. I am grateful for his encouragement, for his continued support of my endeavours, and for all his personal and professional advise. In short, I thank him for being a great mentor.

I would also like to genuinely thank my co-supervisors Andrew Vande Moere and Frank Heidmann for their support throughout the years; Andrew particularly for persuading me to strive for more concise writing, his advise on information aesthetics, and his keen eye on my output; Frank particularly for his encouragement and trust, and his advise on cartography and user studies; and all three for their discussions on visualization research.

In addition, I would like to extend my appreciation to my examination committee Philip Dutré, Hans-Christoph Hobohm, Jan Aerts, Joris Klerkx, and chair Herman Neuckermans for taking interest in my work.

Moreover, I want to acknowledge the support and advice I received from so many colleagues. Foremost, I thank Christoph Kinkeldey for the countless discussions, for proofreading, and for being great company at conferences. A big thank you goes to all my colleagues from FH Potsdam for providing a supportive and cordial working space, and in particular to Boris Müller and Moritz Stefaner for inviting me in, and for sharpening my eye for design. A special thanks goes to my students, sharing my passion and often greatly exceeding my expectations with their projects.

I would like to thank Cyrus D. Khazaeli for supervising my diploma thesis as my first venture in information visualization, and for luring me back into academia by inviting me to teach at BTK Berlin. I am also very thankful to Gillian Crampton Smith and Philip Tabor for asking me to teach at IUAV Venice, and even more for setting a stellar example on how to engage and guide students in a pleasant and fruitful classroom atmosphere. I owe a big thanks to Carlo Ratti for inviting me to the MIT Senseable City Lab to work on visionary smart city projects, and to Kristian Kloeckl, Oliver Senn, and all the others in Cambridge and Singapore for being such great and stimulating colleagues.

Though I was doing – as Erik poetically called it – a *butterfly PhD*, and visited Leuven only every so often, I am thankful for the support and feedback (and ping-pong challenges) from my colleagues and co-students at the HCI group at KU Leuven: Bram, Frans, Gonzalo, José, Katrien, Nik, Robin, Sten, and Sven. I also owe thanks to so many others for feedback and discussions, be it at meetings, at conferences, on blogs ... too many to name them all.

I also want to thank my treasured friends in Berlin and Hamburg, to René, who helped me at any and all times, to Nick, Brendan, Henrike, Ekkehard, and all the others who supported me, inspired me, or simply had to bear my ramblings on some random detail I was working on. Thanks also to my friends and colleagues from the Berlin design community for creating such a stimulating place to live and work.

And last, but definitely not least, my deepest thank you to my family: To my mother Juliane, my father Hans-Georg, my step-dad Peter, my sister Kata, her wife Alfa and their family for their encouragement, their patience, and for nurturing a desire to strive, to question, to tinker, and to not bother too much with a sedentary life style.

Finally, I would like to express heartfelt appreciation to my beloved Anke who was always there for me, helped me sort things out when I most needed it, and brought me back down to earth with her clear head and calm nature.

Danke.

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Chapter 1

Introduction

1.1 Motivation and Overview

The increasing abundance of geo-referenced data goes hand in hand with a growth of interested user groups besides cartographers or urban planners. On the one hand, more and more data is digitally collected from municipal systems and sensors, which leads to substantial new possibilities in analyzing the urban environment for experts in public and private institutions [46]. On the other hand, with the widespread dissemination of online maps, location based services, and mobile navigation devices a large laymen audience is accustomed to using geo-spatial data in everyday life. This led to a steep increase in interactive geographic maps, be it for personal use such as navigation, or for shared usage such as storing photos with their locations. The aggregation and visualization of massive amounts of geospatial data enables the analysis and presentation of urban activities [5], such as visualizing tracking positions of mobile phones to reveal flows of city dwellers moving towards an event location [30].

Interactive or animated maps are used increasingly to reveal facts or stories related to geo-spatial information in various application domains. Interactive visualizations of urban data not only enable experts to improve city planning etc., but enable citizens to discover personally relevant stories. More specifically, data visualizations can help urban dwellers to explore suitable subsets of data, e.g. for their neighborhood, or for the time they are commuting, while playful interactions and aesthetically pleasing design [51] can make such visualizations more attractive and interesting to use.

Problem. While visualizations have been used to make these data accessible, often they are tailored to one specific group of users, typically expert users. Geographic information systems (GIS) enable experts to analyze the data through visual means, but these GIS have been found to be too complex for casual exploration [4]. There is the need for simpler, less complex geovisualizations, in order to engage non-experts to understand data and gain insights. Whether the data is relevant for an individual, or for a larger group, an important aspect of geovisualization for non-experts is the social factor to encourage people to participate in the discourse on the domain. Heer et al. argue that "the adoption of information visualization technologies by lay users – as opposed to the traditional information visualization audience of scientists and analysts" [77] has implications for visualization construction and design. With existing tools it is often difficult to create interactive geovisualizations tailored for a particular domain or a specific dataset [65].

Research Goals. Our general research objective is to facilitate exploring and understanding geospatial patterns, relationships, and trends for wider audience groups by designing comprehensible and easy-to-use interactive visualization systems for time-varying geo-referenced data. The general research question is how to design interactive geovisualization systems in such ways as to incite curiosity and attract non-expert users so they approach the system, explore the visualized data, and ultimately gain insights into the presented domain.

Methodology. Our research approach was guided by an explorative methodology. Within this PhD work, we designed and evaluated three case studies from different domains. For each, we followed principles from a human-centered design approach [69]. With every case study we investigated its domain while following the shared main goal of enabling a casual exploration of geo-referenced data on a large interactive screen displayed in semi-public space. All case studies had in common that the knowledge inherent in the data was relevant for non-experts in a casual use scenario. However, each data set was different in its specifics, and exemplified different aspects of tempo-spatial data. From classic geo-spatial data such as information on buildings and places (Chapter 2), to geo-referenced social network data (Chapter 3), to mobility data based both on authoritative data sources (timetables), as well as sensors and smart phones (passenger data) (Chapter 4). We evaluated each system with user studies, and will summarize and generalize our findings in Chapter 7.

Introduction Chapter Overview. In the following sections, we will introduce the research of this thesis. We will start with outlining the research goals, and formulating the research questions (Section 1.2). Then, in Section 1.3 we will give a thorough background on the research topics, and situate the research within its larger context. We will lay out and explain the approach of our research work, describe the research methods, and give proper justification (Section 1.4).

An introduction of the case studies, their objectives and outcomes will follow, together with a brief description of their specific domains in Section 1.5.1. We will conclude this introduction chapter with an overview of the following chapters of this thesis.

1.2 Research Questions

This thesis investigates how to facilitate exploring and understanding geospatial patterns, relationships, and trends for wider audience groups. We will examine visualization systems of time-varying geo-referenced data on interactive tabletops in order to gather feedback from such audiences. We will investigate how to effectively design such visualizations, how to employ and adapt visualization and interaction techniques, and how to ease the development of such systems.

The context of this research lies at the intersection of the areas geovisualization (see Section 1.3.1), interactive tabletops (Section 1.3.1), and non-experts as target users (Section 1.3.2).

In the remainder of this section, we introduce the following three research questions, which cover the areas of our research:

- **RQ1**: How to visualize multivariate tempospatial data for casual exploration on interactive tabletops?
- **RQ2**: How to visualize multivariate relationships between geo-referenced data?
- **RQ3**: How to support different stakeholders to create tempospatial data visualizations?

While RQ1 is the core research question, all are intertwined and depend on each other. To investigate RQ1 we will design and evaluate multiple case studies, which we will justify below. As visualizations on tabletops for non-experts have specific requirements, as we will explain below, one outcome of their design process is the adaptation and extension of visualization techniques. RQ2 is concerned with a major and recurring challenge, which we will detail in Section 1.4.2. RQ3 enquires into the development of such visualizations, and how supporting the construction of such systems can contribute to answering RQ1 and RQ2. For each research question, we will outline the research problem, the approach, and which chapters it relates to (see also Table 1.1).

1.2.1 RQ1: How to visualize multivariate tempospatial data for casual exploration?

Problem. While geovisualization is an established field to enable interactive exploration of tempospatial data [122], visualizations are often aimed only at experts visually analyzing the data, and overly complex to understand for lay people [4]. As data related to people's surrounding increasingly become interwoven into people's life, visualizing such geospatial data for casual exploration is vital. We investigate how to best facilitate exploring and understanding such data sets for wider audience groups of lay users. We define lay users as people who have no or low levels of expertise in the domain (and neither are experts in information visualization, tabletops or other research areas related to this thesis).

This question entails to explore effective ways of visualizing tempospatial data in interactive ways to reveal patterns, relationships, and trends, and to support different stakeholders gaining insights while engaging and attracting casual users in semi-public settings. This is the core topic of this thesis, and consists of a set of sub themes and questions.

Approach. We will explore the field through case-studies. With each case study we investigate the full design process of domain analysis, design requirements, prototype development, and evaluation in order to approach the research field in a holistic approach essential for real world use. We have publicly exhibited visualization systems to large audiences in exhibitions in order to evaluate with people in real world settings. We have complemented these demonstrations with other established evaluation methods when necessary. We will discuss and reflect these design approaches based on experience within our series of case studies.

Relation to chapters. In the case studies, we approached this research question from different angles, each within their specific domain. We explored how to visualize a) faceted data of urban redevelopment for casual exploration of citizens and urban planners (Chapter 2), b) collaboration between research institutions for casual exploration of scientists in a conference setting (Chapter 3), and c) public transit data for casual exploration of public transit experts and citizens (Chapter 4). Besides these domain related main design goals, with each case study we had a specific question we addressed in the visualization, yet are applicable for casual geovisualizations in general:

- **RQ1.1**: How to facilitate interactive exploration of faceted data for casual users without providing complex user interfaces?

- **RQ1.2**: How to support exploring personal relevant data in such ways to facilitate a social space to discuss insights with others?
- **RQ1.3**: How to provide multiple perspectives into complex tempospatial data for casual users?

We will summarize our contributions in Section 7.2.1, and classify and discuss the case studies in the subsequent Sections 7.2.2 and 7.2.3.

1.2.2 RQ2: How to visualize multivariate relationships between geo-referenced data?

Problem. The aim of visualizing data is not to display properties of a single item, but to allow viewing similarities and differences, identifying patterns and outliers, and to compare items and sets of items with each other. Besides, items can have intrinsic relationships between them, and these relations often have additional properties. Thus, visualizing such relations is a common and important task.

Graphs depicted as node-link diagrams are widely used to show relationships between entities, and are an appropriate way of visualizing graphs with geo-located nodes [79]. However, these result often in visual clutter. Furthermore, these graphs often contain additional information, such as edge weights. Current techniques lack simple ways of depicting edge weights without occlusion.

Approach. In each case study, we investigated how such multivariate relations can be visualized for casual use. Based on these results we generalized some of our lessons learnt, and developed a new technique to visualize weighted connections in linear path graphs.

Relation to chapters. In Chapter 2, we investigate how to visualize relations between scientific institutions with varying strength based on co-authorship. In Chapter 3, we investigate how to visualize relations between scientific institutions with varying strength based on co-authorship. And in Chapter 4, we investigated how to visualize ridership relations between public transit stops. We will describe design objectives, algorithm, and limitations of a proposed technique to visualize weighted connection in Chapter 5. We will summarize our research results in Section 7.3.

1.2.3 RQ3: How to support different groups of developers to create visualizations of tempospatial data for casual use?

Problem. Geovisualizations aimed towards an audience of non-experts may allow exploration as well as communication depending on the specific goals (cf. [25]). With existing tools, it is often difficult to create interactive visualizations tailored for a particular domain or a specific dataset [66]. Currently, there are too few software frameworks, which support efficiently developing visualizations on interactive tabletop and surfaces [98].

Approach. Within the scope of this question, we want to research how designers and developers can be supported to create geovisualizations for lay people, and how to ease the construction of prototypes to explore data sets or novel visualization techniques. More specifically, we want to investigate if and how a library of reusable software components can assist the creation of such visualizations.

- Discuss approaches to support visualization construction.
- Identify and support different user groups from students, to practitioners, to researchers.
- Find an appropriate software architecture to fulfill the contrasting requirements of ease-of-use and flexibility.
- Select a programming environment to suit the targeted developer groups.
- Develop reusable components to facilitate rapid prototyping.
- Verify whether examples and tutorials can act as implicit knowledge storage for best practice and design patterns.

The success of a library can be assessed by having a wide dissemination and acceptance in the community, as well as being used for successful applications [22]. We demonstrate the versatility of our library in use through a collection of examples. We evaluate whether it helped supporting and easing the development for the targeted user groups with a user study.

Relation to chapters. Based on the findings and lessons learnt from our case studies, our research objective is to identify typical tasks developers have when designing visualization systems, and investigate in what ways people use a library. We categorize these tasks into groups, and describe how we support each group.

We describe the design goals, and the design and functionality of such a library in Chapter 6, and discuss how it assists developers to create visualizations. We summarize our contributions and the impact of this library in Section 7.4.

1.3 Background

The main research area of this thesis is situated in geographic information visualization (GeoVis), and converges on the related areas of interactive tabletop and surfaces (ITS), and casual use. After giving brief overviews on each of these, this chapter will outline previous and current research in the overlapping domains.

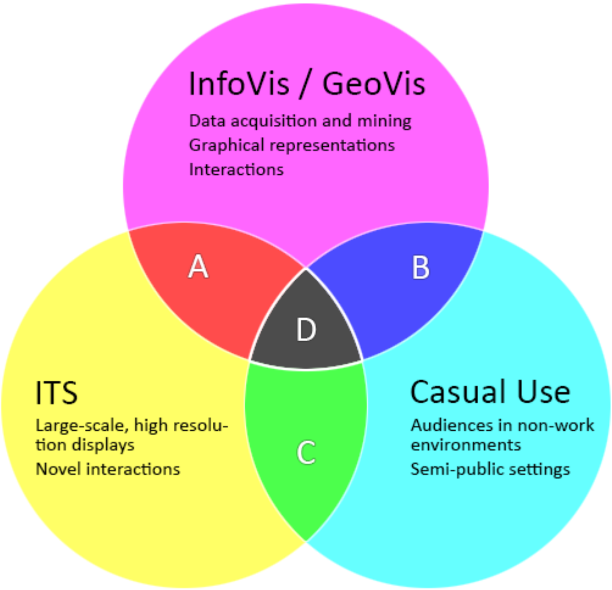


Figure 1.1: The three main research areas, with intersecting fields InfoVis/GeoVis on ITS (A), InfoVis for casual use (B), ITS for casual use (C), and InfoVis on ITS for casual use (D).

1.3.1 Visualization on Interactive Tabletop and Surfaces

Information Visualization and Geovisualization

Information Visualization focuses on graphical representations of data to help people understand and analyze data. The research area utilizes computer graphics and interactions, and investigates how to use visualization techniques to effectively and efficiently reveal the internal structure of the data [187]. In one of the foundational text books, Card, Mackinlay and Shneiderman define information visualization as the "use of computer-supported, interactive, visual representations of abstract data to amplify cognition" [31]. Generally, its aim is to assist humans in gaining insights [169] and solving problems [157].

Traditionally, two distinct modes of information visualization use can be identified: Exploratory and explanatory. The exploratory use entails the analysis of a data set with the goal to build or verify hypotheses. Systems supporting exploration must offer substantial interactivity from filtering to more complex mechanisms such as adapting the visual mapping. The explanatory use entails the communication of knowledge within a data set. Here, interaction might be limited, and the visual mapping pre-defined. These two modes may be seen as opposing ([111], [31]).

While information visualization typically focuses on abstract data [34], geovisualization, or *geographic information visualization* deals with data that has physical and spatial correspondence [123]. However, it covers not only geo-spatial data alone, but also multi-variate geo-referenced data, typically including time-varying properties. Geovisualization stimulates visual analysis of patterns, relationships, and trends, and allows exploration and understanding of geo-referenced information. The research area investigates how to provide tools and methods through which complex, multivariate and location-based data can be visualized in a way to support the synthesis of the data [47].

Interactive Tabletops and Surfaces

In the last decades, computer use was mostly desktop-based. People sit at a desktop, using keyboard and mouse to control the system, which in return displays the interface and its content on a monitor. The research area of *interactive tabletops and surfaces* (ITS) investigates alternative display and interaction possibilities. It consists mainly of two intertwined areas: Large-scale, high-resolution[1] displays, and novel interaction mechanisms for their use.

Two characteristic features of such displays are increased physical size and higher resolution [144]. These displays are substantially larger than the average display from contemporary home or work computer systems [3]. While one feature is the high pixel dimension, due to the large scale they not necessarily have higher pixel density than their desktop counter-parts. One way of resolving this is by assembling multiple monitors, or an array of projectors [144], though these do not result in seamless displays due to the single display bezels. Another approach is to develop new hardware technology with higher pixel density. The physical shape of such interactive surfaces varies widely, and can come as (horizontal) tabletops [136], (vertical) wall-displays [68], or anything in-between. Such hybrids can be tilted (e.g. [137]), or curved (e.g. [197, 199]), or combine horizontal and vertical displays (e.g. [142]).

In recent years, natural user interfaces such as multi-touch, tangible and other physical interaction mechanisms have become more wide-spread. With lower hardware prices, improved sensing technology, and more mature interaction patterns, ITS move into various private and public spaces ranging from museums to hotels to dwelling places [167].

Visualization on ITS

Information Visualization can benefit from interactive tabletop and surfaces, both by leveraging the dimension of large displays, as well as the usability of novel interaction mechanisms [51]. This can lead to more effective and engaging ways to employ visualizations [98]. Some researchers stress the need to further investigate the intersecting areas of visualization design, perception, interaction techniques, and display technologies, and try to catalyze this by highlighting research challenges for designing information visualization on large, high-resolution displays [3].

More specifically to our research, geovisualizations and interactive maps are common applications on large scale interactive displays. Since decades, large, high-resolution displays have been used for geographic information systems [54], or urban planning [99]. In a recent survey on visualization on ITS, Isenberg and Isenberg examined 111 relevant publications[2] [97]. In these, maps “were a particularly prevalent type of information representation”, which according

[1] The term *high resolution* refers to two separate concepts: High pixel dimension, i.e. number of overall pixels on a display, and high pixel density, i.e. number of pixels per unit length (typically pixel per inch, ppi).

[2] Original publication included two case studies of this thesis. Meanwhile, all three case studies papers are part of the survey.

to the authors might probably be because they work especially well on large displays [97]. Meanwhile, only a very small portion of the projects developed custom data representations. Thus, they emphasize the open research question of how to adapt visualizations to ITS.

1.3.2 Casual use

Visualizations for casual use

Traditional information visualization targets an audience of experts with extensive knowledge and skills in a domain, and supports them analyzing specific problems. In contrast, *casual information visualization* targets different audiences, and entails the use of "computer mediated tools to depict personally meaningful information in visual ways that support everyday users in both everyday work and non-work situations" [156].

While the purpose of visualization generally are insights, casual visualization also has additional purposes: to raise awareness, to fuel discussions, or to create a good user experience. Sprague and Tory identified major categories of goals of casual use, from utility to learning to entertainment, or just to alleviate curiosity [174]. The field contains various research topics and challenges unique to information visualizations for casual use [156, 173, 174].

Due to the use of visualization by casual users, more and more non-experts also want to share and create visualizations. Heer et al. state that this adoption of information visualization technologies by lay users affects visualization research, design and development, and define novice, skilled, and expert users as distinct user groups interested in the creation of visualizations [77].

ITS for casual use

Much of the research in ITS focuses on the technical side (display hardware, sensing technology, implementation), yet has strong implications on how people use these systems, both in work as well as non-work environments. While both entail common research areas such as gesture interactions, or user interfaces on large displays, ITS for work focuses on areas such as computer-supported collaborative work [165], or individual versus group use in workspaces [52].

Related to our work is the area of interactive tabletops and surfaces for non-work environments, and more specifically for casual use. These environments typically are either semi-public or public spaces. In this thesis, we did not investigate individual use of small-scale interactive surfaces such as mobile devices. While the distinction between small and large mobile devices start to blur, we focused on large tabletops in order to support small groups of people (as well as due to the technical circumstances at the start of the dissertation).

ITS for casual use span systems in semi-public spaces such as museums (e.g. [88, 142]), or in public spaces such as shopping windows (e.g. [152, 135]). Systems for public spaces are located in openly accessible spaces, and aimed for general passers-by, and systems for semi-public spaces are located within a confined physical space, and aimed at individuals or small groups [90]. These systems often allow getting specific relevant information (such as tourist information, or navigational help), or playfully exploring (such as social interaction, or public games).

1.3.3 Visualization on ITS for casual use

Over the last years, interest in information visualization has increased rapidly [21], and moved from a research topic to mainstream adoption both in commercial and personal applications [77]. Similarly, large ITS systems have been transferred from research labs to public spaces "where they present information and enhance experiences in a highly visual and often interactive way" [83]. Combining these two areas by placing novel visualization systems on interactive surfaces in public settings may foster the use of visualizations to a broader audience beyond the traditional user group of data analysis experts [98].

Over the years, casual information visualization systems on interactive tabletops and surfaces have been designed, and put to use in museums (e.g. [84, 142]), libraries (e.g. [178]), and urban public spaces (e.g. [185]). While first case studies exist, this still is a topical and evolving research area. In a recent visualization viewpoint, Isenberg et al. discuss data visualizations on ITS, and propose a research agenda including technical, design, and social challenges [98]. They also stress the need for more deployments and reports or evaluations of their use [98].

1.3.4 Summary

In summary, ITS seems to be especially fitting for providing information visualization for casual exploration. My work lies at the intersection of these three areas (see Figure 1.1D), and focuses on geovisualizations on interactive tabletops for casual use.

1.4 Approach and Methodology

In our work, we followed an exploratory research approach, and designed and evaluated three case studies from different domains, all guided by the main research question of how to visualize multivariate tempospatial data for casual exploration. We followed an innovative, agile, interdisciplinary research process and incorporated state-of-the-art technologies with state-of-the-art aesthetics in meaningful use cases and scenarios within appropriate domains. Alongside the design objectives for the case study domains, the research was design- (e.g. new visualization techniques, experiments with digital maps) and technology-driven (e.g. new interaction mechanisms with multitouch tabletops). While designing our visualization systems, we created a software library to help us develop prototypes more efficiently and more rapidly.

1.4.1 Case Studies

Case studies are an established method to investigate an information visualization system in realistic settings [153]. They are a holistic approach, which enables researchers to gain a rich understanding of a situational context [32], and strive to achieve realism by studying the tool use in its intended environment [113].

A multitude of evaluation methods exist, each with their own set of advantages and disadvantages. Different methods are appropriate at different stages of the design process, thus Tory et al. argue that a good evaluation process should include a variety of tests all through the development [180]. In contrast to visual analytic tools for experts, evaluating visualization systems for casual use is even more complicated. Pousman et al. argue for the need of evaluating in-situ in order to be able to observe people in a setting where they use such systems naturally [156]. Studies of visualization systems in semi-public spaces consist of observations of people reacting to an installation in a museum [121], or visitors approaching and using an interactive visualization [84].

In summary, the benefit of case studies is that they “report on users in their natural environment doing real tasks, demonstrating feasibility and in-context usefulness” [153]. The drawback is that they are expensive in labor and time, and that results may be neither replicable nor generalizable [153].

In order to resolve or at least mitigate the problem of generalizability, we performed multiple case studies under a common theme. The results of each single case study might be applicable only for the domain they were based in. However, with the identification of common problems and potential solutions for the larger area of tempo-spatial data visualization for casual exploration, we aim to extract more general knowledge.

1.4.2 Visualization Technique

In the process of designing interactive visualization prototypes, we investigated the most effective methods appropriate for the data, the audience, and the objectives, and considered various design alternatives. One design goal of our research was specifically to employ established visualizations in the wild. A design study does not need to have a novel algorithm or technique contribution; instead it often is a well-justified combination of existing techniques [166]. In all three case studies, one of our contributions lies in the description of our design considerations, as well as in the aesthetic and usable composition. Isenberg et al. argue that such research can focus as much on the design of visualizations as on interaction techniques [98]. However, occasionally no suitable techniques might exist for the specific context of our prototype. Even if, these might not be fully fitting for casual use, or for tabletop displays, and must be adapted and/or extended. While this was not the focus of this dissertation, in each of the three case studies (and in many of my other experiments and projects) we needed to create new or adapted methods.

1.4.3 Visualization Construction Support

Constructing visualization systems is complex, both the design as well as the implementation of the actual prototype [93]. In our exploratory research we designed multiple prototypes for our case studies. In early stages of the design process, we developed small-scale visualizations in order to analyze the data, and to be able to discuss tasks and objectives with domain experts. In later stages we implemented visualizations for large tabletops in order to demonstrate and evaluate it with lay audiences. Along the way, we came across common implementation tasks recurring in the different stages. We identified typical design challenges, and created basic reusable software components. After some time, we reflected on this collection of components and best practices, and designed a software architecture aiming to assist us and others developers with similar tasks to construct visualizations. Gradually, this resulted in the development of a software library to create interactive maps and geovisualizations.

1.5 Overview

The core part of this thesis text is a compilation of research publications. Each chapter represents one publication, except for the current and final chapter. We selected five papers out of all the publications I authored or co-authored in the last four years (see Appendix A.4 for all publications).

They consist of three case studies, one technique, and one software library. The have been originally published as follows.

- Nagel, T., Heidmann, F., Condotta, M., Duval, E.: Venice Unfolding: A Tangible User Interface for Exploring Facetted Data in a Geographical Context. NordiCHI 2010, October 16–20, Reykjavik, Iceland. Proceedings of the 6th Nordic Conference on Human-Computer Interaction, pp. 743–746, ACM
- Nagel, T., Duval, E., Vande Moere, A.: Interactive Exploration of a Geospatial Network Visualization. CHI 2012, May 5-10, Austin, USA. Proceedings of the 2012 ACM Annual Conference Extended Abstracts on Human Factors in Computing Systems, pp. 557–572, ACM
- Nagel, T., Maitan, M., Duval, E., Vande Moere, A., Klerkx, J., Kloeckl, K., Ratti, C. Touching Transport – A Case Study on Visualizing Metropolitan Public Transit on Interactive Tabletops. AVI 2014, Como, Italy. In Proceedings of the International Working Conference on Advanced Visual Interfaces, pp. 281–288, ACM
- Nagel, T., Duval, E., Vande Moere, A., Kloeckl, K., Ratti, C.: Sankey Arcs – Visualizing edge weights in path graphs. Eurovis 2012, 5-8 June, Vienna, Austria. Eurovis 2012, pp. 55–59, Eurographics Association
- Nagel, T., Klerkx, J., Vande Moere, A., Duval, E.: Unfolding – A Library for Interactive Maps. SouthCHI 2013, July 01-03, Maribor, Slovenia. Human Factors in Computing and Informatics, Lecture Notes in Computer Science, volume 7946, pp. 497–513, Springer

All selected publications have me as main author, cover research work carried out within the scope of this PhD, and have been published at peer-reviewed international conferences with well-known publishers. The publications are reproduced in an unaltered state, only the layout differs to adhere to the styling of this thesis.

	RQ1	RQ2	RQ3
Case Study 1: Venice Unfolding	x	x	x
Case Study 2: Muse	x	x	x
Case Study 3: Touching Transport	x	x	x
Technique: Sankey Arcs		x	
Library: Unfolding			x

Table 1.1: Relations between chapters and the research questions they examine.

In the following, we briefly introduce each of the case study chapters, which investigate the central research question RQ1, yet also relate to RQ2 and RQ3. We then introduce a chapter on a novel visualization technique to elaborate on our investigation into research question RQ2, and a chapter on a software library to support the construction of geovisualizations (RQ3).

1.5.1 Case study chapters

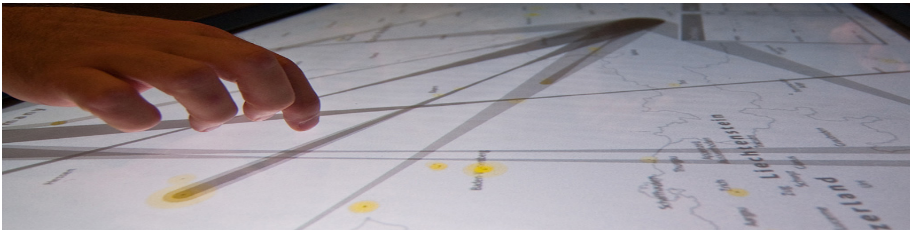
Case Study 1: Venice Unfolding

What: Venice Unfolding is a visualization of urban redevelopment projects, with tangible interactions to support facetted browsing of architectural metadata. It aims to invite citizens and urban planners to explore multi-variate data within the Venetian redevelopment process.

How: On a large interactive tabletop, projects and their relations are shown on a map. A polyhedron acts as physical artifact allowing users to interact with the visualization in tangible way.

Main Objective: Design and evaluation of a novel interaction method consisting of a polyhedron people can tilt to filter and search through the taxonomy, place to select specific projects, and rotate to browse through a project's background information.

Case Study 2: Muse

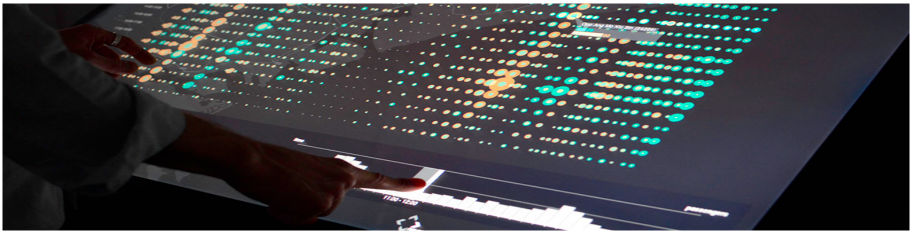


What: Muse is a tabletop visualization of collaborations between research institutions. It is intended to be used at scientific conferences and aims to engage audiences to explore their personal network, as well as to act as casual background to initiate discussion on future collaboration.

How: It visualizes scientific connections between institutions based on co-authorship, and shows the places and their relations on an interactive map.

Main Contribution: How to harvest and enrich metadata from data repositories in ways to show spatial relationship. Multiple in-situ demonstrations and in-the-wild studies with conference attendees. A couple of best-practices / guidelines extracted from a multi-prototype iterative design process.

Case Study 3: Touching Transport

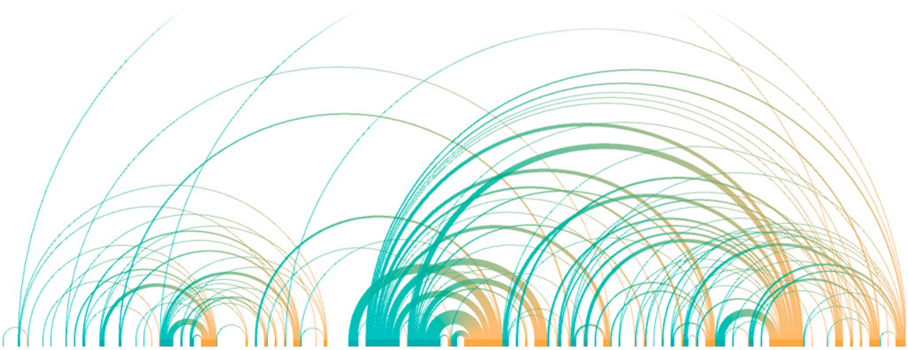


What: Touching Transport is a multitouch visualization of public transit network. It supports the exploration and understanding of complex tempo-spatial data for experts and non-experts.

How: The system provides multiple perspectives of the data and consists of three interactive visualization modes conveying tempo-spatial patterns as map, time-series, and arc view.

Main Contribution: Design and in-situ demonstration of tabletop visualization system. Lab study informed by in-situ observations, investigating how our system supports gathering insights for three different user groups (experts, citizens, and non as control).

1.5.2 Technique chapter: A novel visualization



What: A novel technique creating less visual obstruction when visualizing edge weights.

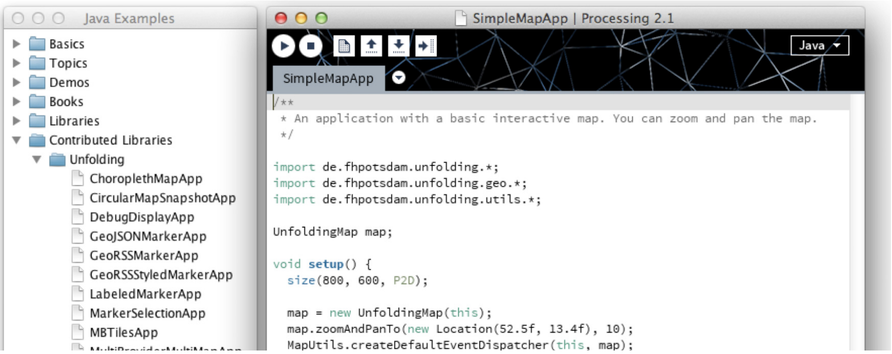
How: Motivated by the common challenge of visualizing relations between geo-referenced objects in all case studies, we identified design goals, and devised the algorithm of a technique to depict weighted connections.

Main Contribution: An extension of weighted arc diagrams to visualize edge weights in path graphs by spreading out arcs, and its demonstration in a case study as a proof of concept.

1.5.3 Library chapter: Support of developing geovisualizations

What: A software library to create interactive maps and geovisualizations. Unfolding provides an API for designers to quickly create and customize geovisualizations.

How: Motivated by the development of the case studies, we collected common task groups, and identified different developer groups. We describe the design criteria, the development process, and the functionalities of Unfolding.



Main Contribution: We provided a tool which support the construction of geovisualizations. The library is an effective means to create state-of-the-art geovisualizations. We also contributed to the field by discussing new audience groups of developers, and reporting on their use of our library.

1.5.4 Thesis Outline

For each chapter, we will name the original publication, specify my contribution, and give an overview of related though not included own publications.

After these five original publications, the thesis will close with the final chapter containing a summary of the research contributions, critical reflections of my work, and final discussion on the current and future state of the art.

Chapter 2

Case Study 1: Venice Unfolding

This chapter was previously published as:

Nagel, T., Heidmann, F., Condotta, M., and Duval, E. **Venice Unfolding: a tangible user interface for exploring faceted data in a geographical context**. In Proceedings of the 6th Nordic Conference on Human-Computer Interaction (2010), NordiCHI '10, ACM, pp. 743–746.

My contribution:

Venice Unfolding was a research project by the FH Potsdam and the IUAV University of Venice. Together with the second co-author, I lead the project on our side, and devised the design objectives together with the third co-author. The prototype was designed and developed under my supervision by the FHP students mentioned in the acknowledgement section. The user study was designed and performed by students under supervision by the second co-author. The publication was co-authored by me with support from the other co-authors.

Other publications related to this project:

Nagel, T., and Heidmann, F. **Exploring faceted geospatial data with tangible interaction**. GeoViz Workshop (2011).

Condotta, M., Nagel, T., and Stefanelli, C. **Browsing and Correlating Architectural and Territorial Data in Tangible Maps: New Knowledge Opportunities in New Learning Places**. Interaction Design and Architecture Journal (IxD&A) 9-10 (2010), 49–62.

2.1 Abstract

We introduce Venice Unfolding, a case study on tangible geo-visualization on an interactive tabletop to enable the exploration of architectural projects in Venice. Our tangible user interface consists of a large display showing projects on a map, and a polyhedral object to browse these data interactively by selecting and filtering various metadata facets. In this paper we describe a prototype employing new methods to communicate territorial data in visual and tangible ways. The object reduces the barrier between the physical world and virtual data, and eases the understanding of faceted geographical data, enabling urban planners and citizens alike to participate in the discovery and analysis of information referring to the physical world.

2.2 Introduction

Work with geospatial data is routinely carried out in groups with users exploring the data in ways according to their different needs. Public participation geographic information systems (PPGIS) "usually call for an open-ended exploration in which users [. . .] examine various issues that relate to their community and locality" [70]. In her literature review, Sieber [170] summarizes they "allow participants to dynamically interact with input [. . .], and empower individuals and groups."

Instead of creating a PPGIS with all the possibilities complex GIS offer, we intended to develop a reduced but user-friendly interactive tabletop visualization with a narrow focus on a specific data set to trigger discussions at town-hall meetings or urban centers. The aim is to support the decision-making process, and to allow active citizens and local stakeholders to impact the directions of their cities. We strived to create an explorative visualization to invite residents to participate in analyzing urban transformation and new projects, helping them to influence the ways limited amounts of money are spent in their territory. For that, we enriched the flux of information, composed of data about projects and conceptual relations between them, with geographic locations. And we tried to lower the barrier to access the data by implementing simple tangible interactions.

There have been several related studies. Ishii et al. [99] describe an Augmented Urban Planning Workbench, which combines physical and digital media for a more holistic design approach. Their conclusions suggest that this method shifts the emphasis away from computer screens by creating an integrated environment in which stakeholders can incrementally create shared understandings. Other studies investigated the utilization of tangible objects for spatial interactions on tabletops (e.g. [9], [108]).

In this paper, we focus on a prototype developed collaboratively by architects, urban planners and interaction designers. We conceived new methods to communicate territorial data in visual and interactive ways, enabling experts and non-experts alike to participate in the exploration and analysis of geo-located data. The paper discusses requirements and design decisions, gives an overview of the visualizations and interactions of the prototype, and concludes with first results of a usability evaluation and an outlook on future work.

2.3 Requirements

We developed a list of specific requirements based on our previous experience in the design of visual exploration tools for architectural contents [142], [176].

- Users should be able to interact directly with the relevant information to be able to control several parameters.
- Navigation of the information space needs to be flexible, according to the choice of users.
- A subtle but permanent guidance giving visual feedback needs to be in place in order to prevent users from getting lost in open environments.
- People should feel invited to participate. The tool shall be social, not as personal and introverted as stand-alone desktop computers, but an open shared information space for collaboration and discussion.
- Size of the interaction space should be large enough to allow multiple users interacting with the visualization. Thus, enabling directed collaborative exploration, as well as to find connections by serendipity when different persons examine the data they are interested in, simultaneously.

In order to enhance knowledge exchange processes, the communication of conceptual networks has to be simple and visual: It allows users to intuitively grasp these conceptual networks increasing both their understanding and exploration activities. In turn, this enhances “analytical strategies for information seeking based on planning, query terms [such as through dynamic filters], and iterative adaptations of queries based on evaluation of intermediate results” [161].

2.4 Prototype

The Venice Unfolding application visualizes the spatial and conceptual relations of 116 architectural projects, enabling users to investigate the territorial transformation of the City of Venice. The prototype is built for a tabletop display, and shows a map as basis layer, which can be navigated by finger interactions. On the map, projects are displayed at their locations, with further metadata visible on demand. A physical object acts as tangible input device, and can be used to select various faceted data and filter the projects. In the design of the object we opted for a shape signifying the interaction possibility to select different facets, hinting to the literal meaning of a “facet”.

Furthermore, we intentionally designed the object to create curiosity by being an interesting physical artifact to invite users to touch and utilize it. If users want to choose a facet, they tilt the object towards that area.

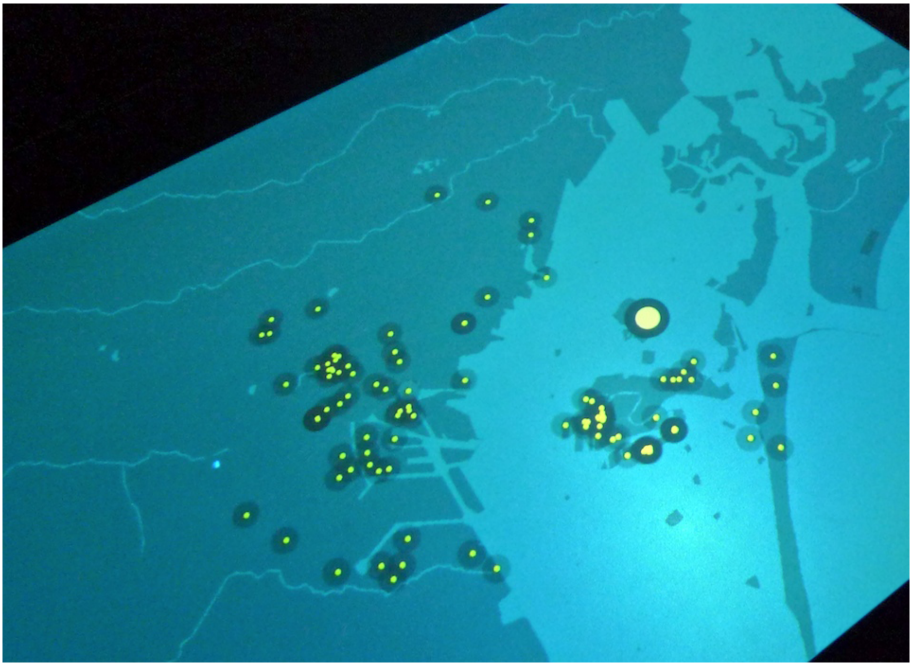


Figure 2.1: Projects displayed on a map of the City of Venice.

The asymmetrical polyhedron consists of one base area and five responsive faces in different shapes, which act as filters to various facets of the data.

Metadata is faceted when it is composed of orthogonal sets of categories, allowing the assignment of multiple classifications to an object. Faceted metadata has been proven to support exploration and discovery [202].

For this prototype we employed facets relevant to architecture and urban planning, i.e. designer, date of construction, functional typology (such as "Infrastructure" or "Residential") and keywords. We picked these classification categories, as they can describe the visualized projects appropriately. For the latter two facets we utilized a subset (selected by architectural experts) of flattened classification terms from the hierarchical MACE taxonomy [130], to reduce the conceptual complexity while still enabling "semantic interoperability among contents" [176]. All facets are used to determine relations between projects based on shared metadata.

2.4.1 Technical Setup

The interactive surface of the tabletop has an area of 1.87 square meters, and a resolution of 29.4 pixels per inch (full HD 1080p). As resolution strongly influences visualizations [95], this relatively low resolution led us to iteratively re-design the interface, e.g. by opting to only display three facet text entries in legible font sizes at a time. The table size enables multiple persons to watch and interact with the visualization, simultaneously. For more details on the construction and technology of the interactive table we refer to [142].

The polyhedral object is roughly 5×6×6 cubic centimeters. Each reactive face of the polyhedron includes a unique fiducial marker printed on the surface. The marker reflects infrared light recognized by a high definition camera inside the table, allowing the system to identify the currently faced-down polygon, as well as the object's position and orientation. This tracking procedure was developed with the reacTIVision framework [104].

Cartographic information depicted through the map comes from OpenStreetMap [149], while Cloudmade [39] provides the image tiles. This allowed us to embed interactive maps fast and effortlessly without the technical setup of a complete map server stack. While the main reason was to customize the map according to interface design necessities, one further advantage is users may contribute and update underlying spatial data. This crowd-source approach may encourage stakeholder communities to participate in discussing territorial problems.

2.4.2 Visualization and Interactions

In the beginning, the map of the whole territory is displayed with all projects represented as markers at their locations (see Figure 2.1). Users can zoom and pan the map to select an area they are interested (by pinching, respectively dragging it with their fingers). Tapping a marker (i.e. touching it with a single finger) selects the respective project and shows its background information and media files, as well as connections to related projects.

The main exploration activity is performed with the physical object, which allows haptic direct manipulation. To select a facet the polyhedral object can be tilted to one of its sides. The edges of the polyhedron are flattened, aiming for an effortless and easy-to-use tilting maneuver.

For the visualization of the data facets we used the metaphor of unfolding a 3-dimensional object, to support users grasping the concept of opening the data set from different perspectives, and “to present a broad overview of the entire collection and to allow many starting paths for exploration” [202].

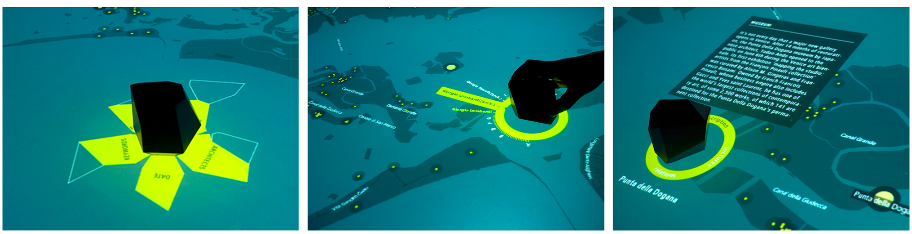


Figure 2.2: Interaction sequence with the tangible object, starting with a) selecting one of the facets, b) choosing a specific entry from the radial menu, and c) browsing through further metadata and media of a selected project.

The polyhedral object can be placed anywhere onto the table’s interactive surface to begin with one of two interactions: (1) Select criteria to filter and display specific projects, and (2) Browse background information of a single project. When a user puts the object onto the tabletop, the facets are displayed, each represented as an unfolded face of the polyhedron (Figure 2.2a). After the user tilts the object onto one of its sides, the entries of the chosen facet are displayed as a radial fisheye menu surrounding the object (Figure 2.2b). The text items are alphabetically ordered and displayed as small ticks, thus visualizing the overall amount of items. By rotating the object the user can now browse through the terms. The currently viewed one is set in large type. Its direct neighbor entries are legible as well, while farther apart ones are blanked out due to space constraints. The user can choose a specific item by moving the object towards its text representation. After a user’s selection, the application filters the data set, and highlights matching projects on the map. If necessary, the map section automatically adapts appropriately, so highlighted projects always fit the whole table surface.

After the user selects a single project, the radial menu around the polyhedron changes to offer background information. The three categories "description", "pictures", and "relations" are shown at North, East, and South position so as to not interfere with the facet item selection (which is at West). Keeping the same interaction mechanism, users select a category by moving the object towards its respective orientation. By rotating the object inside the ring users can explore project information in detail: scrolling through the descriptive text, and browsing through explanatory pictures (Figure 2.2c). Selection of the third category ("relations") activates the project's conceptual network with other projects (Figure 2.3).

Figure 2.3: Exploring relations between projects.

The possibility of showing related projects in a direct visual way is a key feature of the interface. The relations are based on common metadata, for example same designer, similar construction date, or sharing some conceptual classifications according to the taxonomy. When the user selects this modality all corresponding projects are highlighted with their titles on the map, and can be selected to start a new browsing and discovery process through the information network.

2.5 Evaluation

We conducted a formative user study to gather first feedback from users working with the prototype. We recruited four male and two female participants aged 22 to 40 years from the student body and non-research staff of the FH Potsdam. All participants were right-handed and with normal or corrected-to-normal vision. The participants all ranked themselves technically savvy, and all but one had used multi-touch devices before. The participants were encouraged to think-out-loud, while the interviewers were writing down those remarks and their own observations. These sessions were recorded on video and took approximately 60 minutes each.

We asked the participants to execute specific simple tasks, and to fill out a post-test questionnaire on their satisfaction with the tool. The tasks ranged from finding projects of a given architect, to filter projects for a specified keyword, and to browse the media of one project.

While the map and the display of the projects were interpreted correctly, the polyhedral object was not immediately understood by all participants. For browsing through the alphabetical list, all users rotated the object in the opposite direction. Two users did not realize the selection mechanism, and tried to tap the appearing items with their finger. After these initial errors all participants learnt the implemented interactions. Overall, the participants described the prototype as “playful”, “inspiring”, and “liked” the explorative approach, but criticized the tilting mechanism as not sufficiently self-explanatory.

2.6 Conclusion and Outlook

We presented a case study visualizing architectural projects in Venice. First results suggest the tangible interaction with the polyhedron reduces the barrier between the physical world and virtual data, and eases the understanding of faceted geographical data. The presented mechanisms look promising to be used in other domains with tabletop applications enabling users to explore various facets of a dataset in a unified visualization.

In the continuation of our research, we will incorporate the given feedback and refine the interaction design aiming to improve the usability. Currently, we are working on extending the polyhedron with an embedded accelerometer to be able to give visual feedback as soon as the user starts tilting the object, with the intention to ease the discovery of the facet selection mechanism. This also will allow us to provide object shaking as interaction pattern to clear the current selection.

Furthermore, we started first experiments in evaluating the prototype using head-mounted eye-tracking devices, and are planning to test the prototype with different sets of data to investigate whether our conceptual background assumptions are transferable to other domains.

2.7 Acknowledgments

We would like to thank the study participants. We also thank Vittorio Spigai and Luigi Di Prinzio of IUAV, and the City of Venice Urban department for the support given us with the database used as case study. Finally, we thank Jula Lakritz, Nadine Patzig, Sabine Richter, Stefan Rechsteiner, Martin Schissler, Sebastian Schwinkendorf, and Stephan Thiel of the University of Applied Sciences for their significant and essential contribution and their work in conceptualizing, designing, implementing, and evaluating the prototype.

Chapter 3

Case Study 2: Muse

This chapter was previously published as:

Nagel, T., Duval, E., and Vande Moere, A. **Interactive Exploration of Geospatial Network Visualization**. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems Extended Abstracts (2012), CHI EA '12, ACM, pp. 557–572.

My contribution:

Muse was a self-funded research project. Harvesting and cleaning the data was done by me, as well as the development and design of all three functional prototypes. I demonstrated them at three conferences, on an interactive tabletop by a colleague from KU Leuven. The user studies and expert interviews were designed and performed by me. The publication was co-authored by me with support from the other co-authors.

Other publications related to this project:

Nagel, T., Duval, E., and Heidmann, F. **Visualizing Geospatial Co-Authorship Data on a Multitouch Tabletop**. In Proceedings of the 11th International Symposium on Smart Graphics, vol. 6815 of Lecture Notes in Computer Science. Springer, 2011, pp. 134–137.

Nagel, T., and Duval, E. **Muse: Visualizing the Origins and Connections of Institutions Based on Co-Authorship of Publications.** In Proceedings of the 2nd International Workshop on Research 2.0. At the 5th European Conference on Technology Enhanced Learning (2010), CEUR-WS, pp. 48–52.

3.1 Abstract

This paper presents a tabletop visualization of relations between geo-positioned locations. We developed an interactive visualization, which enables users to visually explore a geospatial network of actors. The multitouch tabletop, and the large size of the interactive surface invite users to explore the visualization in semi-public spaces.

For a case study on scientific collaborations between institutions, we applied and improved several existing techniques for a walk-up-and-use system aimed at scientists for a social setting at a conference. We describe our iterative design approach, our two implemented prototypes, and the lessons learnt from their creation. We conducted user evaluation studies at the two on-location demonstrations, which provide evidence of the prototype usability and usefulness, and its support for understanding the distribution and connectivity in a geospatial network.

3.2 Introduction

Physical gatherings at conferences are an important form of scholarly communication, in order to ease socialization, and getting involved in the debate on newest research [168]. One of the main effects for attendees is to be connected to a network of researchers [190], and to establish personal contacts [128]. Our large tabletop display acts as social space for people to gather in a conference setting, be it as by-standers or as active users, and invites them to engage in conversations on location. We opted to visualize research collaboration based on co-authorship data, in order to act as a catalyst for starting casual and opportunistic discussions on the community, and facilitate understanding and reflecting on one's own and others' research network.

There has been a vast amount of research in the areas of bibliometry to extract and specify the metrics of scientific publication and citation networks. Several approaches to visualize these networks have been reported on (e.g. [155], [80]). In contrast, the objective of our case study is not to investigate individual authors and their personal co-authorship networks, but rather to enable analyzing the collaboration network of their affiliations. More specifically, our aim is to direct attention to the spatial relations to enable users to visually explore their scientific neighborhood in order to investigate the characteristics of their network within an existing social setting of a conference.

Geovisualization provides tools for visual exploration of geospatial data, and supports "visually-enabled information retrieval" [122]. The display of geo-positioned objects on a map helps viewers seeing real-world clusters in the visualized data set. The spatial distribution of the data, as well as the visual encoding of data values allows users to detect density patterns. Connections between nodes are based on the semantic relation between objects. Our prototype visualizes bi-directional relations based on a shared data value.

Instead of creating a system with all the possibilities complex geographic information systems (GIS) offer, we intended to develop a reduced and engaging geovisualization with a narrow focus for a very specific use case. In particular, the design of the visualization technique was specifically motivated to facilitate the understanding of geospatial data for a wide audience, including people without expertise in GIS.

Our interactive tabletop visualization is intended to be a walk-up-and-use system. In our case study on research collaboration, the targeted audience mainly consist of attendees at scientific conferences. One of our main design goals for visualization and multitouch interaction was to facilitate first-time users to use the system without training. For this purpose, we created two prototypes aiming to create an easy-to-use interactive geospatial network visualization.

Although it has received relatively little attention in literature, interaction in visualization is one of the main determinants for the quality of a user's dialogue with the data, which ultimately facilitates the understanding and insight into this data. Therefore, the design of the interaction capabilities of our prototypes was based on a set of design guidelines for fluidity in visualization, including: the use of animated transitions, the immediate feedback, the minimalization of indirection, the integration of user interface elements, and never-ending exploration possibilities [51].

3.3 Related Work

In scientometrics, studies have demonstrated the growth of international collaboration in science by using co-authorships (e.g. [35], [63], [120]). One of the objectives is to discover what kind of, how many, and between whom scientific collaboration exists. Studies have shown that geographic proximity is important and does positively influence the intensity and frequency of scientific collaboration [105]. In Börner's Atlas of Science, she states that citation frequency between affiliations decrease the more distant they are [28]. She claims that spatial proximity facilitate building and maintaining personal relationships, which seems to be even more relevant for co-authorship than co-citation networks.

Geo-spatial relations in citation or co-authorship networks have been analyzed by means of visualization (e.g. [12], [148]). As data can be structured in combination with their geo-location in a natural and intuitive way [33] we deem the approach of using geovisualization as very promising. In one study, the top 100 cited researchers have been analyzed by mapping their locations with circles proportional to the number of cited scientists, in order to compare different places [12].

In recent years, several approaches to visually represent collaboration between institutions have been studied. One project used a geographic map highlighting the research collaborations of the Chinese Academy of Sciences with locations in China and countries around the world [91]. Flow lines representing these relations are displayed on a large choropleth map, which is accompanied by six smaller ones, showing collaboration in province-level administrative divisions. In another project a map of scientific collaboration was designed with data from scientific journal aggregator Elsevier Scopus [15]. The map traces the lines of collaboration between cities, which results in a dense and beautiful world network.

We aim to extend some of the insights these static visualizations support, by allowing further examination of the network by selecting geographical areas, and filtering the dataset for exploration of personally relevant sub-networks.

3.4 Interactive Prototypes

The two tabletop prototypes share many characteristics. Both show a world map on the interactive display, with all institutions shown as markers at their geo-locations. The map can be navigated freely, while place markers can be selected to get background information on publication output as well as their relations to other institutions. In the following paragraphs, we describe the data used, the general visualization and interaction, the geographic maps used, and the tabletop. In sections below, we describe the features of the two prototypes, and explain the pros and cons of the approaches.

3.4.1 Data Acquisition

The inter-institutional relationships are based on co-author data, as co-authorship reflects research collaboration between affiliations and countries, adequately [63].

We applied our geospatial network visualization in two case studies on collaboration between research institutions. These case studies are based on co-authorship data as stored within two distinct data sets:

For the demonstration of the first prototype, we used the European Conference on Technology Enhanced Learning (EC-TEL) publication data from the years 2006–2010, to show the connectivity in the scientific TEL community. While the dataset of this younger conference was small, it allowed us to demonstrate a prototype visualizing relevant data to conference attendees. We scraped the publication data from the website of Springer, the proceedings publisher. For the demonstration of the second prototype at the ACM Conference on Hypertext and Hypermedia (Hypertext) 2011, publication data from the ACM digital library of the years 1989–2011 were used.

In both cases, we needed to harvest data on co-authorship using our own algorithm, as existing aggregation services such as Bibsonomy [89], citeUlike [37], or Mendeley [129] do not provide affiliation data. Thus, we used Web-Harvest [196] to collect author affiliations and their postal addresses directly from the publisher of the conference proceedings. As the information originally is provided by the authors, using various languages, formats, and accuracy levels, we needed to apply different aggregation and unification heuristics, trying to reduce unintentional duplicates or other skewed data entries.

3.4.2 Cleaning the Data

First, the affiliation line is split up into the affiliation name and the address, to allow a better unification of affiliations, and to display a shorter and more readable name in the visualization. The simplistic, language agnostic approach was to concatenate all text segments up to and including the last segment containing one of a set of specific keywords, selected for high probability of matching institutional name segments.

Secondly, the affiliations were unified, based on the similarity of the name. The affiliation text for the same institution may be in English or in the original language, may include abbreviations or be written out, and the order of organizational subparts may change between different papers. Thus, in order to identify affiliation duplicates the similarity algorithm needed to have the following characteristics: (1) Strings with small differences should be recognized as being similar. (2) It should be robust to changes in word order. (3) It should be language independent. We used the algorithm developed by White [198], which calculates how many adjacent character pairs are contained in both strings. We considered all pairs of institution names more similar than the threshold of 0.7 to be matches, and all pairs less similar to be non-matches.

The chosen threshold value was based on our manual review of the dataset, to be fitting for our specific set of institution names.

Finally, the institution's address was geo-coded. Besides geo-locations, the corresponding countries were stored to allow comparing country-level statistics, later on.

3.4.3 Visualization & Interaction

Users are able to select the region they are interested in by panning and zooming the map through slide and pinch finger gestures (see Fig. 3.1). Even though more complex map manipulations are possible, we chose this simple interaction approach, in order to enable the user to concentrate on the map, with less efforts.

Figure 3.1: A pinch gesture to zoom the map.

Affiliations are represented by circular markers at their geo-location. The size of a circle indicates the overall amount of papers written by authors from that institution. In the lower left corner a legend explaining the size of the circles is shown (see Fig. 3.3).

Users can select a country by tapping on the background map within its political borders. That country gets selected, and additional information is shown in a data widget in the lower right corner. The number of papers, authors, and institutions over the years are displayed as bar diagrams (Fig. 3). As long as the user has not tapped anywhere, the widget displays a semitransparent message to communicate this interaction pattern. When two countries are selected the prototype displays the diagrams besides each other, allowing the user to compare them. A second country is selected only if users tap on a different country.

By tapping on a circle, the name of its institution is displayed atop, and relations to other institutions are shown. Relations between institutions are visualized by connecting lines between the two markers. We adhered to the schema most visualizations of social networks use, in that actors are represented as dots, and relations among them as lines [56]. The visual lines connect two institutions transparently, to not obstruct the underlying map or markers.

3.4.4 Geographical map

The cartographic information shown in the background map originates from OpenStreetMap [71], while MapBox [125] provides the image tiles. Thus, we were able to customize the map according to interface design requirements, and embed it as interactive maps fast and effortlessly without the technical setup of a complete map server stack.

3.4.5 Tabletop display

The geo-visualization is shown on an interactive tabletop with multitouch capabilities. With the large interactive surface, the user not only views and manipulates data on a single user system, but operates in a collaboratively created and used information space.

In this setting, co-located users, who may or may not be associated with each other, explore the visualization together (Fig. 3.2). Users can arrive or leave at any time, and have the ability to interact as an individual, or as a member of a group with similar interests, goals or attitudes. Cooperative interaction can involve periods of tightly coupled activities by groups with similar but diverging goals, alternated with more loosely coupled individual work. Such collaborative threads can close, split off and merge repeatedly.

The interactive surface of our tabletop has a resolution of 50.8 pixels per inch at full-HD (1080p). With a dimension of 0.96 x 0.54 meters multiple persons can gather around to watch and interact with the visualization, simultaneously [142]. The table was designed to be approachable and usable from all sides. At

Figure 3.2: Discussion among conference attendees in a semi-public setting.

the same time, the table is small enough, that a person can reach all areas on the interactive surface when he stands on one of the wider sides.

3.5 Design Approach

We designed two working prototypes, following an iterative development approach [145], and demonstrated the first at the EC-TEL conference 2010 in Barcelona, Spain, and the second at the Hypertext conference 2011 in Eindhoven, The Netherlands. The iterative design was chosen in order to refine the spatial network visualizations, and to increase the usability of the interactions. This iterative design, test, redesign, retest cycle allowed us to incorporate feedback from experts and users in all stages. Such an iterative process based on measured use and user comments leads to continuous refinement of the prototype and its features, and helps to make sure that the interactive visualization addresses real needs.

While the iterative methodology itself is well-known, we deliberately went with an open procedure. In all stages, our design decisions were mere offerings to the users. While based on proven work and prior findings, the whole process was strictly guided by feedback from actual users. Besides validating the interactions and visualizations, it was equally important to learn about the goals and needs of conference attendees.

The demonstration of the prototype at conference locations as well as the collection of feedback from conference visitors lead to us being able to improve the overall experience in direct response. It further allowed us to incorporate the physical and social context of use (cf. [69]).

3.6 Evaluation Methodology

With both demonstrations, we carried out on-location usability studies with selected conference attendees. We also conducted a preliminary user study on the legibility and distinguishability of visual connection styles. The results from these evaluations helped us to further improve the application to its current state.

We designed the studies as pluralistic usability walkthrough [20], with a semi-structured interview guiding them. Semi-structured interviews give participants the possibility to comment with a degree of freedom [115], but provide more focus than the conversational approach.

As one of the objectives of the visualization is to offer exploration in a collaborative, public setting, we conducted the user study on location, at a place where potential real users are. The advantage of this setting is that it "report[s] on users in their natural environment doing real tasks, demonstrating feasibility and in-context usefulness" [153]. Furthermore, it allowed us to observe affective reactions to the prototype, and to ask participants about their experience in a public setting.

We ran the study with one interviewer, and one participant executing the tasks and answering the questions. However, we did not preclude others from watching, or to later join the discussion. This allowed us not only to imitate a live setup at a conference, but also to observe social interactions among the user and bystanders.

We asked the participants to execute selected tasks, and to answer questions concerning the understandability of the visualized information. The five tasks ranged from basic interactions such as navigating to a place, to selecting and exploring institutions, to comparing institutions or countries with each other.

For the two prototypes, these tasks were adapted to the respective data set of conference proceedings, and used comparable affiliations and places (i.e. locations with similar properties and/or visual representations). Slight differences were acceptable, as we were not measuring efficiency.

We observed participants performing the tasks, which allowed us to get a better understanding of the aspects of the problem than if they only have described it verbally [115]. The participants were encouraged to think aloud, while the interviewers were writing down those remarks, as well as their own comments.

Finally, we invited the participants to fill out a post-test questionnaire on their opinions and preferences to determine the perceived usefulness of the visualization. The questionnaire was based on the Useful Satisfaction and Ease-of-Use Questionnaire [119]. We used a 5-point Likert scale with items ranging from "strongly disagree" (1) to "strongly agree" (5). This survey was done privately and anonymously.

The complete sessions took approximately 20-25 minutes each.

3.7 First Prototype

The affiliations are shown on a light gray background map. Selected affiliations show their name as label, and their relations as gray connections. A visual connection is shown if authors from two institutions published at least one paper together. There is no indication of the number of collaboratively written papers. Instead, the visual style of the connections varies depending on the overall amount of published papers of both the selected institution and the related institutions (see Fig. 3.3).

3.7.1 Evaluation

We recruited nine male and three female participants, aged 27 to 52 years, from the attendees of the EC-TEL 2010 conference. The participants had normal or corrected-to-normal vision, and all but one were right-handed. All 12 participants had prior experience with touch devices, with eight having further experience with large-scale multi-touch devices. To assess how the participants related to this specific dataset, we asked for experience and number of publications. With a median of 2 attendances and a mean of 1.5 submitted papers to the EC-TEL conference we assume the participants were engaged adequately to have some personal interest in exploring the visualization. Seven participants immediately used two finger gestures to zoom and pan the map. While initially two participants tried to double-tap to zoom, two tried using only one finger, and one searched for navigation buttons, they all switched quickly

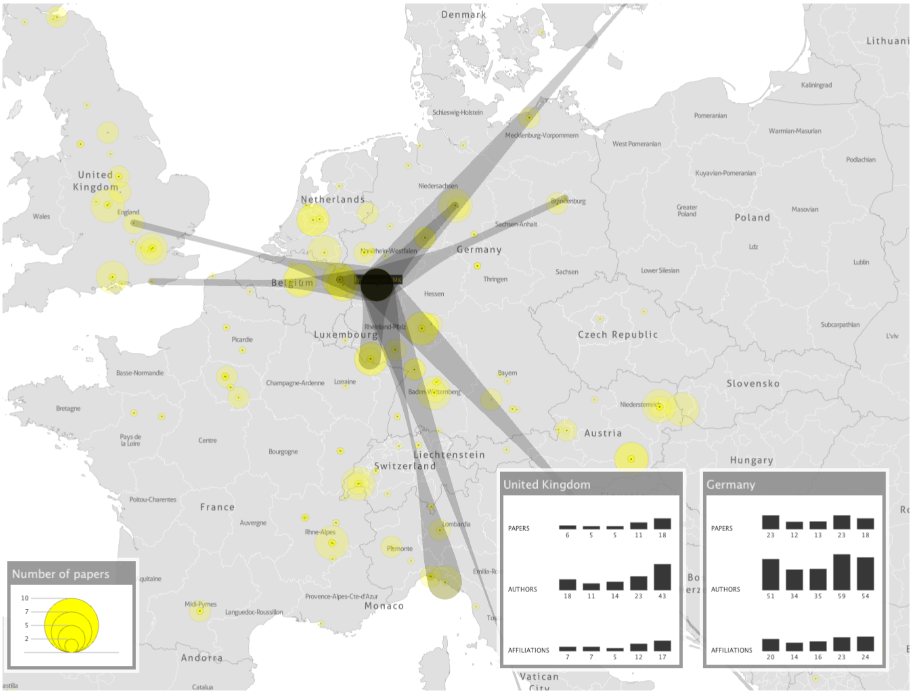


Figure 3.3: First prototype with one selected institution and its co-authorship connections.

and without cues from the interviewer to the correct interaction mechanisms. We grouped and unified the feedback and extracted the top three issues, which we discuss in the subsections below. Several improvements are proposed to respond to the detected problems. We identified some further issues, which either only few participants had problems with, or – in one case – were trivial shortcomings: The connection edges were displayed on top of the institution labels, which leads to illegibility if an institution has many connections. This flaw was pointed out by 10 participants, and has been fixed by simply inverting the ordering. Minor issues users commented on included difficulties understanding the switching behavior of the country comparison widget (2 participants), the meaning of the year bars (2), and the legend for the circle sizes (1).

Quality of Connections Unclear

The connection between affiliations does not directly represent the number of co-written papers. However, the visual style of the connections varies depending on the overall number of published papers of both the selected institution (with outgoing edges) and the related institutions (incoming) (see Figure 3.4). We chose this visualization technique with the aim to give an indication which of the connected institutions is the most important one. Evidently, this was not the most adopted interpretation by the users. 10 out of 12 of the participants were under the impression that the connection width visualized the number of co-written papers. Seven participants commented on this, with four suggesting it to be changed with high priority.

Various methods for displaying the strength of these inter-institution relations can be employed; (a) showing the number as text label on the connection, or (b) mapping it onto a graphical variable of the connection representation (e.g. color, or thickness).

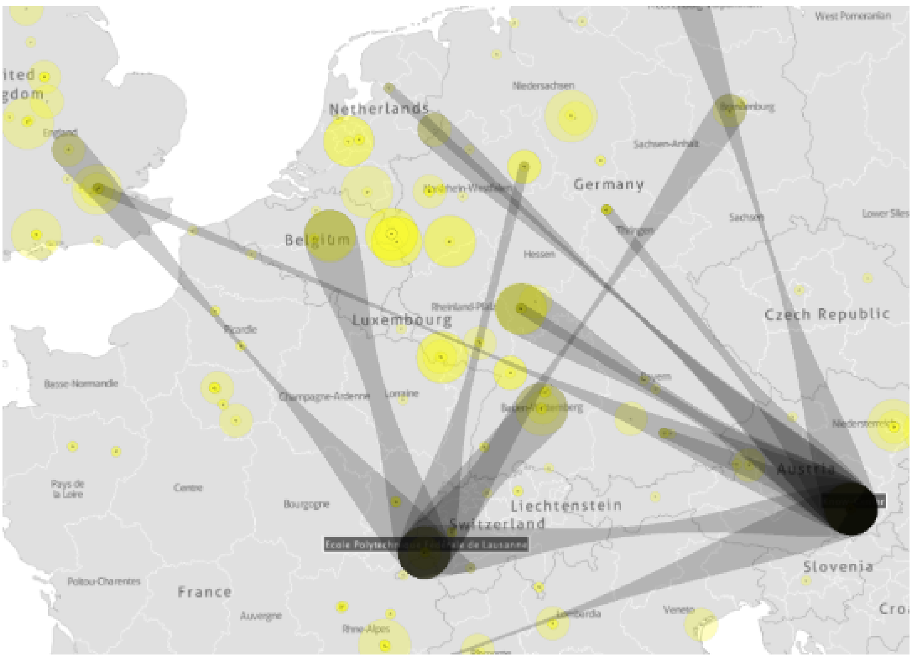


Figure 3.4: Co-authorship network of two selected institutions.

Insufficient Geographical Features

We chose a map style which displays only few geographical features. The aim of the prototype is to allow exploring and understanding the geo-spatial relations. Thus, the objective of the map is to support general recognition, while being discreet enough to not hinder the display of the data and interface layers. However, half of the participants had at least some problems in finding places mentioned in the usability walkthrough[1]. This was unexpected, and even though we did not design tasks to examine this issue, specifically, four tasks involved navigating to or identifying a place on the map. To improve the findability of geographical places, we considered the following possible solutions: (a) Add text field to search for geographical features. This would require some kind of text input, which implicates higher interaction complexity. (b) Display list of selectable countries. This might reintroduce visual clutter, and would only allow filtering on a country level. (c) Display more place names on the map.

Allow Single Selection of Multiple Affiliations on Same Location

Tapping a marker selects an affiliation, and shows its name as label, as well as its connections to other affiliations. When asked to select an affiliation, all participants tapped on its marker (with 1 participant double-tapping), and managed to select it correctly. However, users had difficulties selecting a single affiliation if multiple ones are at near-by positions, due to the visual overlapping of markers. This was due to two reasons: First, insufficient address data provided by the harvested authors, thus not all affiliations could be accurately determined and geo-positioned with high precision. Therefore, two institutions from the same city could have been placed at the exact same location (the place's center according to the gazetteer). Second, users also had difficulties when two institutions with separate locations were in close proximity. 10 out of 12 participants could not select "Graz University", where three other affiliations were overlapping. To be able to select one of these by tapping on it with a finger, users first had to zoom in to a level where the markers became distinct. Solving both issues might be possible in two ways. By (a) changing the layout algorithm in such manner that the markers do not overlap anymore. With many near-by institutions this could lead to a too heavily skewed geo-spatial positioning. Or by (b) clustering the markers, and expanding them, when the user taps on them.

Usefulness and Satisfaction

Post-test, we asked the participants to fill out a questionnaire on their satisfaction with the tool, with 11 out of 12 participants responding. The participants

[1] The interviewer showed or confirmed the correct location, after the participants finished their navigation, to allow them trying to answer follow-up question.

had great fun (median: 5), and were strongly satisfied using Muse (median: 5). Most agreed or strongly agreed (median: 4) to the statement that the visualization helped them to better understand research collaboration. Overall, the participants strongly found the prototype to be useful (median: 5) and easy to use (median: 5).

3.8 Second Prototype

In the next iteration, we tackled the identified issues, reviewed papers reporting on related studies, and tried to overcome the problems by implementing one of the solutions proposed above. In order to allow correct data interpretation, and the comparison of different markers, the visual encoding is based on a power law suitable for symbol size discrimination [118]. We based the size of the text labels on findings of Ashdown et al [7], and selected a font size of 14pt for a display resolution of 50ppi. Furthermore, we added a visual distinction between selected and non-selected markers.

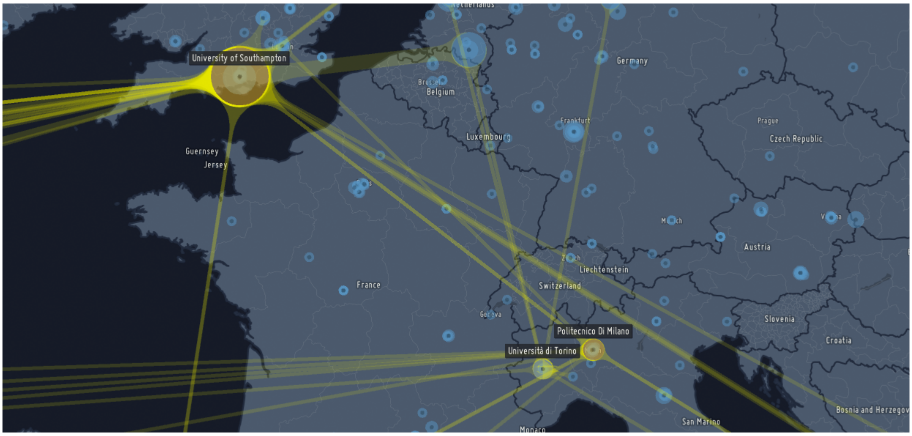


Figure 3.5: Second prototype with selected and non selected institutions.

Visualize Quality of Connections

Relations between places are visualized by connecting lines between the two markers (Fig. 3.5). In our case study, a visual connection is shown if authors from two institutions published at least one paper together. The thickness of the connections varies depending on the total number of co-published papers of the selected institution with the related institutions. The results of a user study with an earlier prototype lead us to adapt the visualization to map the strength of a connection. The visual style was chosen for good legibility, while the smooth junctions between the circle marker and the connection aim for an aesthetically pleasing look of connectedness [150]. It was also chosen to make it easier discernible whether a connection merely passes under a marker, i.e. points to another affiliation in the same direction. Through the enlargement of the line in proximity of a marker, it aims to make it clearly visible to which marker the line belongs to. The lines connect two institutions transparently, in order to not obstruct the underlying map or markers.

Improve Map Style and add Geographic Places

We used a map showing more labels of geographical places. We adapted the map design to fit to the rest of our visualization according to color schema and typeface. It has to be verified whether the least demanding technical and cognitive solution of using a more detailed map style will be sufficient to help users find the places and institutions they are interested in.

Enable Selection of Single Marker in a Cluster

Places are all shown at their original geo-location, which results in overlapping markers for institution in close proximity. In contrast to non-geographic layout strategies, where a positioning algorithm may prevent collisions, we opted for a visualization technique in which the visual distribution shows spatial patterns. However, precise selection of small or overlapping markers is difficult due to the *fat finger problem* [160]. This was also evident in the behavior of the participants in our user study of our first prototype. Thus, we designed Exploding Menu, a mechanism to ease the selection of near-by institutions.

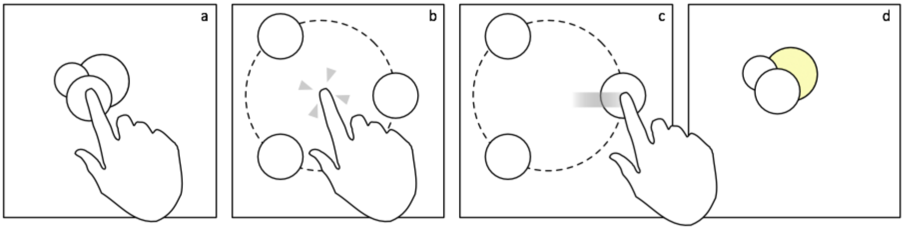


Figure 3.6: Selecting an institution from a group of near-by marker.

In the beginning, multiple overlapping markers are shown at one location (Fig. 3.6a). When a user touches the marker cluster, a radial menu appears with all the markers evenly laid out on a concentric ring (Fig. 3.6b). The user slides (or taps with a second finger) onto the markers, which will be highlighted (Fig. 3.6c). When the user releases his finger atop one menu item the marker gets selected, and is shown at its original position (Fig. 3.6d). To select another marker of the same cluster, the interaction pattern has to be repeated. The same mechanism can be used to deselect institutions. In our prototype, all markers represent research institutions with their number of publications mapped to the size of the marker. In Figure 3.7a, multiple markers with various sizes are shown at the south of Great Britain. The user taps on the cluster, and the radial menu is displayed with a black transparent circle, darkening the background map and other markers (Fig. 3.7b). Note that the marker proxies in the menu are shown in their original sizes. When the user slides over of the proxy markers, the name of the institution is displayed (Fig. 3.7s) in order to support selecting the correct affiliation. After the user selects one marker the radial menu disappears, and the corresponding institution is shown with all its connections (Fig. 3.7d).

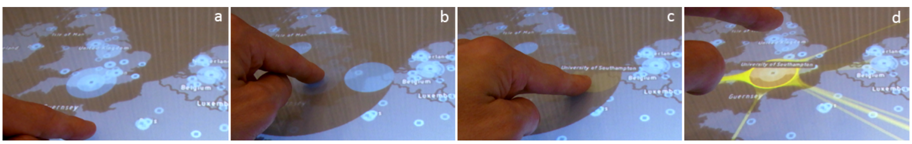


Figure 3.7: Selecting an institution from a group of near-by markers in the second prototype.

3.8.1 Social Interactions

The tabletop visualization induced not only human-computer, but also human-human interaction. We observed a variety of ways in which attendees got in touch with each other. Users were:

- Starting discussions. When users were exploring their personal network, observers commented on connections to their own institution, or on shared collaborators. Often, this resulted in lively conversations.
- Exploiting the visualization for story-telling. For example, one user was narrating the history of his institution over the last 15 years and its contribution to his field to fellow researchers, while selecting affiliations and pointing to connections.

- Engaging other users. When one or more persons were actively interacting with the table, passers-by were more inclined to stay for a bit, watched the visualization and the interactions, and eventually tried it out themselves.

3.8.2 Evaluation

At the Hypertext 2011 conference, we conducted a similar usability walk-through as for the first prototype, and investigated if the changes improved the usability of the visualization. The evaluation study involved nine participants, two females, and seven males, aged 23 to 44 years. The participants had great fun (median: 5), and were satisfied using Muse (median: 4). Most agreed or strongly agreed (median: 4) to the statement that the visualization was useful in reflecting on the Hypertext community, and that is was very useful (median: 5) in understanding the geospatial spread of the research network. Overall, the participants strongly considered the prototype easy to use (median: 4).

3.9 Conclusion and Outlook

We presented two working prototypes for exploring geospatial networks. We designed these as walk-up-and-use systems with comprehensible geo-visualization, so that interested stakeholders can use it without much effort. It was designed for a large multitouch tabletop, in order to invite users to participate and engage in discussions at a semi-public location. In our case study, the application visualizes co-authorship data of conference publications. The geographic distribution of the institutions, as well as the visualization of the number of publications has been found to be easily understandable. Through interactive filtering, the users were able to explore the relations between their affiliations and other institutions, and could gather insights into the collaboration network in their domain. The results of our usability studies, and the feedback gathered from the questionnaire demonstrate that this is a promising approach to exploring geospatial relationships in scientific networks. In designing the system, we learnt valuable lessons, which we summarize below.

3.9.1 Rapid Adaption of Map Styles

We did not expect the problems participants had with orienting themselves on an interactive world map. One design challenge is to balance the style and detail levels of a geographic map for geovisualization, providing enough details to enable users to recognize places, and not so many details that they interfere with the information overlaid over the map. Having the ability to adapt the map style rapidly to our dataset was very helpful.

3.9.2 Visual Style of Weighted Connections

The design of the connections between institutions is based on a preliminary user study. As we are not aware of any controlled user study on the legibility of weighted connections, we emphasize the need for further research in this field.

3.9.3 Acceptance of Multitouch Interaction

Compared to other recent studies ([133], [48], [191]), the participants of our studies had more previous experience with multitouch devices. This was reflected in their behavior, as few were having problems with the map navigation. For a user group of tech-savvy persons, we thus feel it is by now quite safe to deploy multitouch interaction in large-screen visualizations.

3.9.4 Radial Menu for Dense Geospatial Data

Our solution for densely positioned markers on a multitouch tabletop used a technique similar to existing ones. However, applying a solution for imprecise finger selection in the context of geospatial data was novel.

3.9.5 Design Process

The iterative design with demonstrations at different conferences was helpful in gathering continuous feedback, but also helped to create a more flexible visualization for different data sets (e.g. finding solutions for dense geo-data). In this way, our pragmatic, iterative process was very effective and we thus feel confident to encourage others to quickly demonstrate early prototypes in the target setting, and constantly refine the techniques used. We applied several existing techniques, ranging from multitouch interactions to network visualization, and adapted them for the context of geo-located co-authorship data visualization on a tabletop. While many of the techniques used are well-established, we see their aesthetic and usable composition in a conference setting as a successful design case study.

3.9.6 Outlook

We used the radial exploding menu to solve overlapping map markers in a different visualization (i.e. enabling the precise selection of bus stations in a public transit application). In a next step, we are going to evaluate how well this technique can be transferred to other domains, and how well it performs compared to alternative selection methods. To guide our selection of the visual mapping indicating the strength of a connection between institutions, we conducted a preliminary user study on various display styles. Currently, we are planning an extended and more general user study on weighted edge visualization.

3.10 Acknowledgements

We like to thank all participants of our studies. We also like to thank the anonymous reviewers for their valuable feedback, and Bram Vandeputte for providing an interactive tabletop.

Chapter 4

Case Study 3: Touching Transport

This chapter was previously published as:

Nagel, T., Maitan, M., Duval, E., Vande Moere, A., Klerkx, J., Kloeckl, K., and Ratti, C. **Touching Transport – A Case Study on Visualizing Metropolitan Public Transit on Interactive Tabletops**. In Proceedings of the International Working Conference on Advanced Visual Interfaces (2014), AVI '14, ACM, pp. 281–288.

My contribution:

Touching Transport was a research project by the MIT Senseable City Lab. Together with a colleague, I aggregated and analyzed the data. I was responsible for the objectives and conceptual design of the system, and implemented the prototype. I designed the user study, performed one part in Belgium, and supervised two in Singapore. The publication was co-authored by me with support from the other co-authors.

4.1 Abstract

Due to recent technical developments, urban systems generate large and complex data sets. While visualizations have been used to make these accessible, often they are tailored to one specific group of users, typically the public or expert users. We present Touching Transport, an application that allows a diverse group of users to visually explore public transit data on a multi-touch tabletop. It provides multiple perspectives of the data and consists of three visualization modes conveying tempo-spatial patterns as map, time-series, and arc view. We exhibited our system publicly, and evaluated it in a lab study with three distinct user groups: citizens with knowledge of the local environment, experts in the domain of public transport, and non-experts with neither local nor domain knowledge. Our observations and evaluation results show we achieved our goals of both attracting visitors to explore the data while enabling gathering insights for both citizens and experts. We discuss the design considerations in developing our system, and describe our lessons learned in designing engaging tabletop visualizations.

4.2 Introduction

In recent years, more and more urban data is digitally collected from municipal systems, sensors, and services. Various commercial initiatives in the field of smart cities from large technology companies such as IBM or Siemens work on new possibilities of analyzing the urban environment for experts in public and private institutions. However, the question has been raised how to better involve the general public. Hill makes a case for active engaged citizens in order to unlock the potential of technology in a city [81]. While the increasing dissemination of mobile devices and location based services enable citizens employing urban data for tasks such as getting directions or finding a restaurant, these tools often lack supporting free-form exploration that can empower people to gain more general insights. In the larger process of working towards an informed discourse on smart cities, we deem reaching out to both experts and citizens with a tool that facilitates understanding of a city as an important step. One way of achieving that is to publicly exhibit visualizations of urban data in an urban demo. These *urban demos* [110] aim to provide visual and interactive access to information concealed in large urban data sets, engage public and industry partners in such operations, and collect feedback and ideas from users.

In this paper, we introduce Touching Transport, a case study enabling casual exploration of urban mobility in Singapore through a set of visualizations on a multi-touch tabletop. Our aim is to enable users to discover personally relevant stories and explore suitable subsets of data, while making visualizations more attractive and easy to use through playful interactions and a visually engaging design. Touching Transport is part of the LIVE Singapore! project [110], whose objective is to develop technologies and interface modalities to collect, combine and distribute large urban real time and historic data. In this case study, we focus on public transit data as it has various tempo-spatial characteristics typical in urban data, and is of interest to a wider audience.

After exhibiting our system at a symposium, we followed the semi-public deployment with a lab study informed by the exhibition to evaluate how and what kind of insights users get, and how they differ between different user groups.

In the following sections we will describe our design goals, introduce the system and explain our design decisions, report on public deployment and user study, and discuss our findings and lessons learned.

4.3 Design Goals

Experts from Singapore's land transport authority were continuously involved in the development through expert interviews, design goal discussions, and feedback rounds for visualization experiments. Furthermore, the design requirements were informed by case studies on tabletop visualization for exhibitions [82, 84, 96, 178], and our own previous research [139, 140]. We will describe the goals, explain how we aim to achieve them, and provide an overview on related work for each. The first two are general design goals of the urban demo, which influenced the latter three concerned with specific requirements for our system. As Touching Transport is intended for casual exploration at an exhibition, our emphasis is on attractive visual design, and simple interactivity, while still allowing different views into the data set.

Enable access to data for different user groups We see it as beneficial to bring together various stakeholders, and to bridge the gap between experts and laypeople for engagement regardless of their background. Interactive visualizations are an established way to communicate complex data to a larger audience [29]. They can provide a common language for different user groups. Visually, it should be appealing and easily understood without oversimplifying or distorting the information. Data needs to be personally meaningful to users for them to be explored in a casual context [174]. An interactive visualization of public transit should enable citizens to discover personally relevant patterns, for instance by looking at the time they are commuting, or by highlighting the areas around their neighborhood. Lastly, the system should employ interaction methods to support different exploration styles [84] in order to be usable by both laypeople and professionals with varying expertise.

Support gathering insights Informing citizens allows them to discuss public transit, and more generally participate in the debate of urban mobility. A side goal in our urban demo is to encourage users to express ideas and wishes. Our visualization system thus should support users in identifying interesting aspects, formulating questions, and ultimately gaining insights. In their recent position paper, Isenberg et al. [98] argue that data visualization on interactive surfaces can help making insight formation more attainable. Designing our system for a large tabletop aims to make data more accessible due to the ability to show detailed visualizations and to provide simple interactions.

Entice curiosity We aim to engage a broader audience and invite them to explore the system by enticing curiosity with attractive visualizations and large-scale tabletops. Interactive tabletops with large displays are seen as appealing to novice users [18], attract people's attention in public spaces [96], and support more casual visualization settings [98].

Visual and interface design are guided by principles of information aesthetics [114], with the goal to provide accurate data representation with easy-to-use interactivity. Aesthetics not only concern the visual form, but also aspects such as originality, innovation, and other subjective factors comprising the user experience [188]. While the novelty of a technique or system is not a value per se, it has been shown that novelty in design is an important factor to elicit aesthetic response from users [92]. Our goal was to use an attractive visual language resulting in a system easily understood and enjoyed by the users.

Provide casual exploration Our system is intended as a walk-up-and-use system so users can casually explore the data in an exhibition scenario, and aims to support *contemplative usage* [156] in a semi-public setting. The system should offer simple touch interactions so users can explore the data without learning complex gestures [98]. This lowers the cost for initial use [174]. Thus, we selected basic interaction methods based on well-established techniques fitting for tempo-spatial data. To invite users exploring the data for longer, the system should provide fluid interactions including high responsiveness and smooth view transitions [51]. Overall, we aim to provide an enjoyable user experience in order to engage visitors. And when they are accustomed and more experienced with the visualizations they might investigate urban mobility in more depth.

Offer multiple perspectives Multivariate data in the domain of urban mobility has many interdependent properties. Our goal is to enable users exploring the various facets, and discovering spatial and temporal patterns of public transit [53]. Thus, our system is intended to provide different visualizations, each offering a specific perspective into the data set. The challenge is to offer multiple linked views without being perceived as too complex in order to not discourage users from exploration [192].

4.4 Touching Transport

Following our design goals we implemented Touching Transport as a functional prototype for a tabletop with multi-touch capabilities[1]. It was built with Processing and the Unfolding Maps library. We developed it in an iterative design process, including various visualization experiments, discussions with experts and test users, and incorporating results therefrom into the system. In the following, we will describe the data set, the visualizations and interactions of the prototype, and discuss our design considerations.

4.4.1 Public transit data

In Singapore, passengers pay the distance-based fare by tapping in and out on boarding and alighting subways and buses. These actions are continuously recorded by smart card readers, and collected by the Land Transport Authority (LTA), the government agency responsible for road traffic and public transport. The data set consists of (i) geospatial (stations, routes, etc.), (ii) temporal (schedule, headways, etc.), and (iii) anonymized passenger data (tap ins and tap outs). From this, we derived further information such as origin-destination paths for each ride.

We used a subset from the various sources available within the Singapore public transport system, and settled on bus data for the prototype. With over 2 millions passengers per day, Singapore's bus network is an integral part of the system. We selected a sample for eight routes with different characteristics (e.g. express lines with few stops) to reflect a broad range of usage. These criteria were based on discussions with experts from the transport authority, and allowed us to examine the applicability for a set of transit data with different properties.

[1] See video at http://youtu.be/wQpTM7ASc-w.

4.4.2 Three interactive visualizations

Our system consist of three interlinked visualization modes, each supporting to look into different aspects of the data. It enables users to actively explore Singapore's bus network, and see where passengers get on and off, how people travel between the island's areas, and the way these patterns change throughout the day. While an interface at the bottom of the screen provides data filtering mechanisms, the most prominent part of the screen contains one of the three visualizations. Together with a large full-HD screen display, this design of showing a single visualization aims to attract casual users through its simplicity.

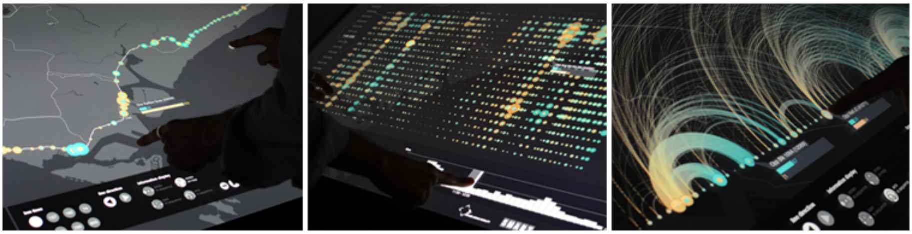


Figure 4.1: Multi-touch tabletop with (a) map, (b) time-series, and (c) arc visualization of passenger data.

Map View

The map view shows passenger data for a selected bus line on a background map of Singapore (Figure 4.1a). For each stop boarding and alighting passengers are visualized as glyph consisting of two circles. The map view enables the understanding of passenger behavior in geo-spatial context, from analyzing and comparing single stops, to clusters of stops with similar characteristics, to neighborhoods and larger urban areas.

Time-Series View

The time-series view displays multiple charts of the same bus line for different times (Figure 4.1b). Each row shows all bus stops for a specific time of day. In a row, the stops of a bus line are displayed sequentially, with boarding and alighting passengers shown for each stop. The resulting columns visualize passengers for a single bus stop over time. Thus, users can observe different times at a glance, and identify tempo-spatial patterns, e.g. locate geo-spatial clusters of stops with similar properties over time.

A feature of this visualization is its adaptability to varying time ranges. Users can adapt the time range to see finer or coarser grained data aggregations. The number of rows (and the time span used for aggregating the displayed data) depends on the selected time range. Thus, users can identify hour-based temporal patterns, e.g. at what time a bus line begins getting crowded, as well as compare longer term ranges such as morning vs afternoon rush hours.

Arcs View

The arc view visualizes rides of a bus line (Figure 4.1c). Each arc signifies passengers traveling from one station to another, with the arc thickness indicating the number of passengers. This visualization enables users to see passenger flow, as well as connectivity of bus stops based on actual bus rides. The number of passengers are double encoded as arc transparency, so that the most frequented bus rides are easily discernible. Now, the characteristics of bus stops become visible, e.g. a stop with many thin arc connections, or a public transit hub with some strong connections.

4.4.3 Visualization Design Considerations

For displaying boarding and alighting passengers on the map, we use concentric circles both being scaled according to their value. We used a diverging binary color schema with turquoise for boarding and orange for alighting. In order to ease learning for casual users, we used the same encoding in the time-series view. While various other time-series graph techniques exist this ensured consistency.

While both map and arc modes support animating through time, the time-series view shows how passenger behavior evolve over time in a single view. We decided on the small multiples technique [181] which has been shown to be more effective than animation [162], and more efficient for comparisons across time series than combinations in one chart [101]. In order to reduce visual clutter and to support focusing on the sequential nature of a bus line, a linear layout for the bus stop sequences has been applied in this view. We opted against an equidistant positioning, where the screen distance between each two stops would have been equal, and chose a distance-based layout algorithm, where the screen distance between two stops is relative to their geographical distance. In that way, users still can recognize spatial groups of stops (e.g. city center), or low density line segments (e.g. express routes).

The arc visualization uses the same linear layout with the same glyphs per stop below, with the arcs showing directed rides above. While the results of a user study on visualizing directed edges [87] suggest using tapered connections, we could not apply a visual mapping with varying thickness as this was used for encoding the number of passengers. Thus, we mapped the direction to color gradient, with the same color schema as in all other visualizations, which also keeps consistency in regard to color coding.

4.4.4 Interactions

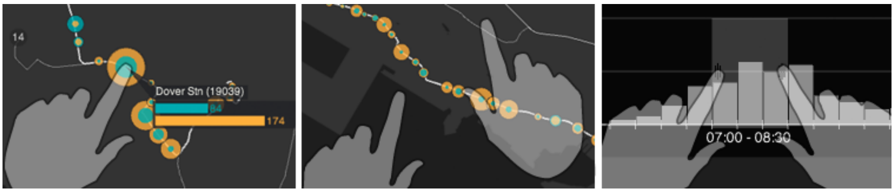


Figure 4.2: Multitouch interactions: (a) Tap to select a bus stop, (b) free-form map manipulation, and (c) dual finger time range adaptation.

Touching Transport supports direct view manipulation as well as auxiliary controls. Users can directly interact within the visualizations, as well as filter the displayed data in the bottom bar, such as to select line direction, or change the time frame and duration. These interactions were based on well-established touch gestures, design patterns for data visualizations, and studies for map interactions [73].

Direct Interactions to select areas and stops

In all three visualizations, users can tap on one (or multiple) bus stops to get details-on-demand with information on the stop and bar charts plus precise values for detailed comparison of the passenger data (Figure 4.2a). In the map view, users are able to select a region by panning and zooming the map with basic finger gestures. Users can drag to pan, rotate to re-orient, and pinch to zoom the map (Figure 4.2b). Even though more complex map manipulations are possible, we opted for simple navigation patterns in order to keep interaction complexity low.

Auxiliary controls to filter data and time

The bottom bar is visible at all times. A legend shows color coding, and visually explains how the data is mapped to its visual representation (Figure 4.3b).

Tapping one of the bus route buttons (Figure 4.3c) selects the respective line in the main visualization. All data is shown with the currently selected filters applied.

The timeline contains an integrated histogram for passenger load and fluctuation (Figure 4.3e), and provides three functions: animation control, time selection, and time range selection. Tapping on the play button starts an animation through the day, giving users a quick impression of temporal travel patterns. Dragging the slider allows selecting any time of the day, for instance to compare morning and evening rush hour. Furthermore, users can investigate different time clusters, altering the range dynamically in 30 minute intervals by adjusting the time range slider (Figure 4.2c). This results in visual aggregations of the equivalent time interval. All time filtering methods update the displayed data in all visualizations. All passenger data glyphs are updated instantaneously, and always reflect the currently selected time range. Their visual properties switch to the next state in an animated transition enabling users to visually track the change, and to easier identify changes in the behavior of passengers.

Figure 4.3: The interface with a) the main visualization (here: map), and the bottom bar containing b) legend, c) bus filters, d) visualization selector, and e) time range slider.

4.4.5 Switching visualization modes

Users can switch between the three visualization modes (Figure 4.3d). Showing one visualization at a time provides a simple entry point to exploring the data. We did not opt for the more classic approach of having multiple coordinated views [40] in order to reduce visual complexity, and not overload a casual user with too much information. In their study on serendipitous discoveries through information visualization, Thudt et al. [178] used multiple views, describe how some of their users felt affected by its visual complexity, and suggest showing only one visualization at a time as a potential remedy. Hence, in Touching Transport only one visualization is displayed in the main screen area. Yet, all three visualizations are interlinked. Selected bus stops in the main view, as well as all data filters chosen in the bottom panel stay consistent in all modes to maintain context, and to enable comparing the same data in different views [192].

When a user switches to another visualization the application animates between the old and the new view. These transitions support the perception of changes between different data graphics [76]. When, for instance, a user switches from arcs to map view, the arcs fade out and the background map fades in, while the visual representations of all bus stops animate to their new position, resulting in the whole route morphing from linear to geographical order. In this way, our system supports users understanding patterns in different views while keeping the spatial context.

To summarize, the goals of the three visualizations are (i) to show spatial patterns, and provide an interface to select areas of interest, (ii) to show tempo-spatial clusters, and allow comparing different times at a glance, and (iii) to show flows of passengers, and connectivity between bus stops and urban areas. Switching between these lets users focus on one view, and still enables them to select the best fitting one in order to gain insights based on different data properties.

4.5 Deployment at exhibition

Touching Transport has been exhibited at an urban mobility symposium at the National University Singapore (see Figure 4.4). Open to researchers, civic employees, and invited citizens, this allowed us to informally observe usage in a non-study setting.

In two days over hundred visitors interacted with our system. The multi-touch table had been set up with a slight inclination in order to attract passers-by.

Figure 4.4: Visitors exploring Touching Transport at an exhibition in Singapore.

Many visitors noticed the large screen even from a distance, and approached to look at the visualizations. Some people first watched it for a while, some directly started tapping the surface and exploring the system. We noticed how some users tried simply touching the screen without any apparent target, assumedly to see if the system is interactive. These were more inclined to explore it further when the map was shown, as this view reacts wherever the user touched the screen.

Visitors had have few problems interacting with the visualizations, were able to switch bus lines and view modes, and dragging the time slider. Although our system is intended for single user interaction, the large interactive screen attracted visitors when others already were gathering around the table. We have observed this honey pot effect [26] independent from whether the earlier visitors were only watching and/or discussing, or already actively exploring the system.

Visitors seemed to like the visualizations based on their facial expressions or their feedback in informal discussions. We also observed persons coming back and bringing friends and colleagues along to show them specific stories they had found earlier. Urban demos act as a catalyst bringing together actors from different fields, and enabling them having an informed debate. We have seen various discussions taking place around the tabletop, often within groups of strangers.

Exhibiting Touching Transport at the symposium was a success from our and our partners view: (i) Members from the LTA have expressed their wish to deploy the prototype in the foyer at their main office, as they highly liked how visitors were attracted to the tabletop. (ii) The LTA has asked us since to help bring an extended version of the system in-house. We did not expect this as our system was intended for casual information visualization, and the authority possess and utilize their own specialized analytic tools. They explained that our visualizations were more engaging to use, and that multi-touch interactions could lower the access barrier for non-IT experts. (iii) Currently, Touching Transport is exhibited in our lab in Singapore, and demonstrated to visitors to act as starting point for discussing the value of data visualizations in developing smart cities.

4.6 Evaluation Study

Information visualization systems for visual analysis commonly aim to provide expert level insights. Visitors in exhibitions may not have clearly defined questions in mind, but explore visualizations based on spontaneous interest [96]. We observed visitors investigating some questions and hunches while playing with the system in the exhibition. In informal discussions we learned they occasionally arrived at insights about specific parts of urban mobility. We found it difficult to record users gathering insights in an exhibition setting as we observed visitors exploring Touching Transport contemplatively. Even when discussing their findings with others, users not necessarily explained their inner monologue. Thus, after the first public exhibition, we designed a user study to investigate in detail how participants use the system while following ideas and questions. We evaluated how Touching Transport supports different user groups, collect what kind of insights users could gain, and verify that different levels of understanding of urban mobility can be reached. We report on the setup, the participant groups, and insights and satisfaction results in this section.

4.6.1 Study design

The study consisted of five parts: (1) The introduction with explanation of the study and the system, (2) a period to freely explore the application to get accustomed with it, (3) the main part where the participant had to come up with insights, (4) a questionnaire to measure satisfaction, and (5) an open discussion for further feedback and suggestions. For parts (2) and (3) we asked the participant to think-aloud, and recorded the audio, while the interviewer observed and recorded the behavior of the participants, and how they interacted with the system. Then, we asked for three insights in three separated sub-sessions of 5 minutes each (and not for just insights in one large session). We intended the three sub-sessions to encourage participants to come up with different findings and/or to use different visualizations.

Each session had one participant. The study was performed in a lab setting, i.e. a room with the tabletop with adjusted light settings and no disruptions. This was done due to allow participants to discuss occurring usability problems, and to motivate reporting more expansive insights via the think-aloud method. Overall, including the (4) post-test satisfaction survey and the (5) open discussion, a session took between 40-60 minutes.

4.6.2 Participants

We tested Touching Transport with 27 participants from three user groups: citizens with knowledge of the local environment (LOC), experts in the domain of urban mobility (EXP), and non-experts with neither local nor domain knowledge (NON). For the first group (LOC), we recruited eleven members from our institution in Singapore (five members of non-research staff and six researchers from other groups). For the second group (EXP), we had six participants from the transport authority. For the third group (NON) we recruited ten students from KU Leuven, a university in a medium-sized European city, with majors in computer science or architecture. Overall, we had 6 female and 21 male participants, aged 18 to 40 years (median: 28).

All participants had prior experience with touch devices, and eight (29%) with large-scale multi-touch devices. They had to self-assess their experience with data visualization, and their knowledge about Singapore and public transit. Expert participants had most experience with visualization, and highest knowledge of public transit in comparison to the other two groups. Experts also estimated their knowledge about Singapore highest, with local citizens second, and Leuven students last. The results are according to our expectations and verify the classification of our user groups.

4.6.3 Insights

To verify whether users were able to gain more advanced levels of knowledge, we followed the suggestion of Vande Moere et al. to also request reports of meaning instead of only asking for facts [189]. We codified and classified insights participants made (see Table 1) while exploring the data into one of the following three categories, and for each describe exemplary insights participants made.

Basic insights

The first category consists of insights into elementary spatial and visual properties. Participants understood the shape of Singapore and its topological features. They could employ the map to relate visual representations of bus stops to their positions, and understand spatial relations such as estimations of their distance. All participants were able to identify starting and ending stops of a line. Furthermore, they recognized outstanding stops of a bus line, and for instance found the ones with large amounts of passenger flow. They were also able to compare two elements in a single visualization, and for instance identify the lesser used bus stop out of two.

Medium insights

The second category consists of insights into more advanced spatial patterns, and basic tempo-spatial patterns. Participants were able to recognize spatial clusters of similar bus stops. Furthermore, participants compared different elements over time, and were able to see basic commuting patterns. Most participants could correctly deduce dwelling and working areas, based on the amount of passengers boarding in one and alighting in the other in the morning hours. Even participants from NON with no local knowledge could identify areas in this way. Participants found the morning peak to be shorter in time, while the evening peak to be spread out by using the time slider, and analyzing the temporal patterns in the passenger histogram. Some participants went on and inferred that this might be due to a wider duration of time in which people leave the office, or are active at night such as running errands or having dinner before retiring for the day.

Advanced insights

The third category consists of insights into more complex tempo-spatial patterns. Here, participants needed to filter the data, for instance by updating the time-

Table 4.1: Insights in each category per participant group.

	Basic	Medium	Advanced	Total	Average
NON (10)	16	8	4	28	2.8
LOC (11)	12	17	7	36	3.3
EXP (6)	4	5	12	21	3.5

range or selecting different bus lines. In this way, they could identify which of multiple bus lines had most passengers at a specific time. Some also used this to further investigate commuting patterns, and discovered how these are inverted in the evening. Participants from Singapore (LOC and EXP) used their local knowledge to identify transfer stations, such as bus stops which are nearby metro stations. Five out of six expert and half of the citizen participants were able to associate movements with areas of Singapore. Some created hypotheses on more specific reasons for passenger flow, for instance that afternoon people travel towards VivoCity, a shopping mall in Singapore.

Furthermore, advanced insights were gathered by comparing the three different visualizations. Participants switched between views to investigate if there were relationships between spatial areas. They were for instance able to see that a specific stop (whose large glyph on the map indicated many alighting passengers) was getting passengers from various stops in the arc view, and deduced that these were passengers riding from their homes towards a transport hub. Participants from EXP were able to apply their expertise and linked the visualized data with specific prior knowledge in order to gather more advanced insights.

Summary

These results suggest our system empowers audiences with divergent backgrounds acquiring a better understanding of urban mobility. Overall, our prototype supports users understanding public transit by getting various insights. In our study, non-expert participants were able to gather a general understanding, citizens a deeper sense of their city, and experts higher levels of insights.

4.6.4 Satisfaction

At the end of the study participants completed a brief post-test satisfaction survey with 21 questions. The survey was based on Lund's USE Questionnaire [119], and used a 5-point Likert scale ranging from Strongly agree (5) to Strongly disagree (1).

Most participants found Touching Transport useful, and agreed or strongly agreed it helps them understand public transit in general (8/10 NON, 6/11 LOC, 4/6 EXP). They were satisfied with the system and its ease-of-use, found it fun to use (24 out of 27), and aesthetically pleasing (26 out of 27) (see Figure 4.5 for details). While the results for all three groups were mostly similar, some areas had differences between groups. Firstly, citizens (LOC) were less

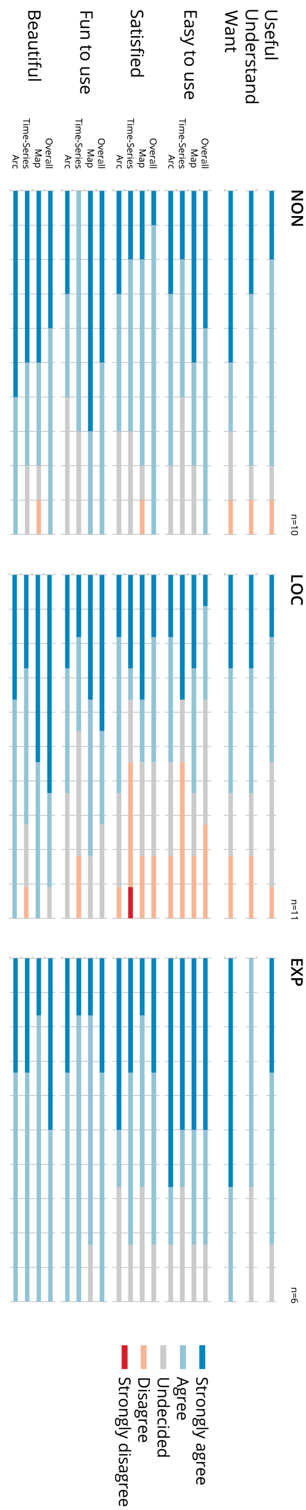


Figure 4.5: Questionnaire results for each user group as normalized stacked bar chart, grouped by agreement (blue) and disagreement (red). The lower charts each show four bars for overall system, map, time-series, and arc visualization.

satisfied with the ease-of-use of the overall system and with each visualization compared to the other groups (3.18 vs NON:4.4, EXP:4.3). One explanation is that our citizen participants had lower prior experience with data visualization. Secondly, all groups agreed to the statement the overall system was fun to use, and beautiful. However, the fun-to-use results varied in regard to the different views. Non-experts (NON) preferred the map the most (4.7 vs EXP: 4.0, LOC: 4.1), while experts favoured the time-series (EXP: 4.2 vs NON: 3.7, LOC: 3.4). As both groups rated the ease-of-use for the map visualization equally, this difference could indicate that non-experts prefer familiarity as they are most accustomed to reading and interacting with maps. On the other hand, experts in the field of public transit seem to prefer abstract visualization methods as it allows them to view more complex aspects of the data.

4.7 Discussion

In the following we discuss and generalize some of the lessons we learned in designing our system in order to inform future case studies with the goal of enabling insights into complex data sets.

Crafting aesthetics: Visual style and Responsiveness

In the field of information visualization there typically is a distinction between systems with a high appeal to communicate stories to a general audience on the one hand, and expert systems to support analyzing data and generating insights on the other. While visualizations in public exhibitions have been studied for casual users, our goal, in contrast, was to enable both experts and citizens gaining insights. The focus of our research was to employ established visualizations adapted to a specific set of urban data. Our contribution lies in their aesthetic and usable composition, and the description of our design considerations.

We tried balancing appeal and accuracy in our visualizations. A visual design with the sole goal of being aesthetic may have a negative impact on readability of precise data values. While multiple expert participants autonomously verified the general validity of our visualizations with their prior knowledge, the intent of casual visualizations is not to come to crystalized conclusion [156], nor exact qualitiative estimation of values for each visual element [96]. Based on people's insights we conclude that our system enables people to understand different patterns correctly. We have shown that it is possible to design an exploration tool that helps a diverse range of users gaining new insights, while attracting casual users with an appealing style.

In both the exhibition as well as the lab study, users were pleased with the fluidity of the interactions, and liked the highly responsive interactivity. Some users expressed their joy about how “snappy” the time slider felt. Touching Transport supports traversing the visualization pipeline with such performance that every filtering of the data or adaptation of the view is instantly reflected (<0.3s) in the graphical display. While it might be difficult to provide immediate response for voluminous and complex datasets [164], investing time and effort in the technical implementation of the system contributes to a enjoyable user experience. Our study results show that carefully designing for performance fosters keeping people engaged with a visualization system in a casual setting.

In summary, Touching Transport has been found to be enjoyable and aesthetically pleasing, and to foster an engaging user experience. Thus, we underline the importance of craft in designing high quality visualization systems.

Multiple coordinated vs single modal views

Touching Transport shows one visualization at a time, rather than all three simultaneously, in order to lower visual complexity for casual users. We observed users switching views to verify a hypothesis about the displayed data, for instance from arc to map view (and vice versa) in order to understand the spatial properties of the visualized bus route. While we did not evaluate through a comparative study whether the benefit of coordinated multiple views in visualizations outweighs the possible distractions they might create [77], with our case study we demonstrated that switching modes work, and can provide multiple perspectives to support obtaining insights. Moreover, the cognitive load of switching views can be lowered with animation. Participants in our study highly liked the transitions between the three visualization modes, and also found it to ease following currently focused data elements. We believe the trade-off of mentally maintaining context is worth the simplicity of a single view. Having one view at a time allowed us furthermore to attract users with one visualization they are familiar with. In our case we utilized the map view as simple entry point to invite visitors to start exploring.

Exhibiting prototypes as part of the design process

A further contribution are the results from both a public deployment and a controlled evaluation study of the system in use. In our design process of creating and evaluating an urban demo, our in-the-wild study primed the lab study. Our contribution lies in the reflection on why we chose this methodological setup, and in the systematic study with three groups of users. We described the differences and similarities in their behaviour, and the varying levels of insights they made.

Citizens and non-experts expressed their wishes for similar visualizations helping them to improve personal travel, while experts asked for having such system for visual analytics to support both planning and real-time control. The fact that users propose such features demonstrates that the system works for idea generation. Our urban demo helped people think about yet new ways of understanding public transit that go beyond the system's current possibilities.

4.8 Conclusion

With our case study on public transit data, we demonstrated how interactive visualizations on tabletops can contribute to the emerging field of smart cities. The three visualization modes facilitate getting different perspectives on the data set, while the fluid interactivity integrates them into a unified user experience. Together, they provide people visual and tangible access to information about the public transit network, and enable understanding some of the vital dynamics of their city. A deployment at an exhibition and the results from our user study suggest that our design goals were largely met: visitors were attracted to the system and casually explored the data. Participants of our study were able to obtain insights, ranging from understanding basics such as transport hubs to more advanced such as commuting patterns.

While supporting concrete citizen participation is an important subject, it was beyond the scope of our research. In this paper, we argue that a well-designed system visualizing urban data can inform citizens and enable them to gain insights. Our intention was to create an urban demo to publicly exhibit visualizations in order to encourage discussion and gather feedback on mobility. Yet, our application is but one step in the larger process of bringing together different stakeholders of a city, and ultimately encouraging participation.

We see the lessons learned to be generalizable for other tempo-spatial data sets aimed at a diverse audience. Within Live Singapore, we are currently developing a system allowing citizens to combine and explore different urban data sets.

4.9 Acknowledgments

We would like to thank Oliver Senn for his excellent support in data preparation and analytics. We also thank the participants of our user study, and the Singapore Land Transport Authority for providing data and expert feedback. LIVE Singapore! is a project in the Future Urban Mobility (FM) group at Singapore-MIT Alliance for Research and Technology (SMART).

Chapter 5

Sankey Arcs - Visualizing edge weights in path graphs

This chapter was previously published as:

Nagel, T., Duval, E., Vande Moere, A., Kloeckl, K., and Ratti, C. **Sankey Arcs – Visualizing edge weights in path graphs**. In EuroVis - Short Papers (2012), Eurographics Association, pp. 55–59.

My contribution:

This technique was ideated and designed by me. I conceived the algorithm, and implemented the demonstrator. The publication was co-authored by me with support from the other co-authors.

Other publications related to this project:

Nagel, T., and Duval, E. **A Visual Survey of Arc Diagrams**. Poster Abstracts of IEEE Conference on Information Visualization (2013).

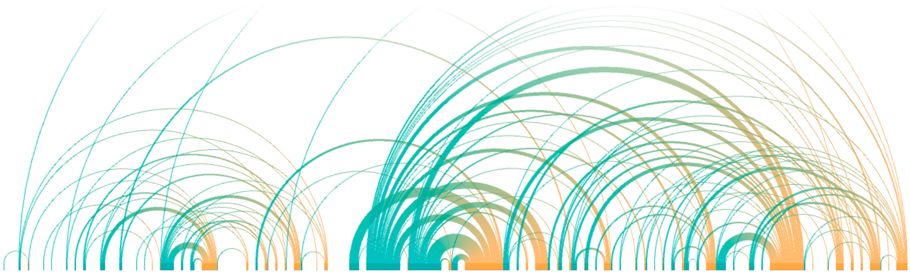


Figure 5.1: Sankey Arcs

5.1 Abstract

Arc diagrams allow exploring relations and their strength between sequential nodes. Previous solutions suffer from displaying all arcs at the center of a node, which can lead to visual obstruction. We present a new technique, which extends the arc diagram technique by laying out the weighted edges of a node adjacent to each other. The aim of our Sankey Arc technique is to improve clarity, to enable users perceiving and comparing weighted edges in path graphs. The technique is illustrated using a dataset on travel paths in a public transit network.

5.2 Introduction

Arc diagrams are an established method to visualize relations between nodes in a simple path graph, which are laid out in one dimension. They have the ability to display multivariate node data, as well as edge properties. Weighted arc diagrams display the strength of relations, revealing the relative and proportional connectivity weight between connected nodes, as well as clusters of connections between neighborhoods.

Weighted arc diagrams represent connection weight as arc thickness, and display all arcs of the same node on top of each other. This may lead to a seemingly complex graphical structure, thus concealing some of the information encoded in the diagram. Furthermore, overlaid arcs of varying width tend to overemphasize nodes with a few strong connections.

One solution is to encode in- and out-weights in an additional glyph, for instance as bar graphs or – more compact – as node size. While this facilitates comparing the nodes and their properties, it does not allow comparing the edges, and introduces further clutter.

In this paper we present Sankey Arcs, a novel visualization technique to visualize relation quantities between ordered nodes. The contribution of this work is an extension to the existing technique, in an aim to display edge weights with less obstruction. It builds upon arc diagrams, which visualize weighted connections in simple linear graphs, by displaying vertex strength as well as the total weights of incoming (in-weight) and outgoing edges (out-weight). This enables users to perceive and compare weighted edges in path graphs.

Vertex strength measures the weight of nodes in terms of the total weight of their relations [11]. Analogous, in-weight measures the total weight of all incoming, and out-weight the total weight of all outgoing connections.

In this paper, we identify the design goals, describe the implementation, and discuss the advantages and limitations of our technique. As a proof of concept, we present how we employed Sankey Arcs in a visualization of public transit data.

5.3 Related Work

Wattenberg introduced arc diagrams as a visualization technique for highlighting repeated subsequences in sequential data such as text or music [193]. Since then, arc diagrams have been applied in different domains, from e-mail threads [106], to command chains [8], to influence relations [45].

The technique also has been extended in various ways. It has been expanded to cover other data structures (e.g. to visualize hierarchical data [143], [67]), visually modified to encode additional properties (e.g. color-coded to show categories [58]), and enhanced by additional functionality (e.g. interactive filtering [36]). In their survey on visualization techniques, Heer et al. describe arc diagrams more generally as “one-dimensional layout of nodes, with circular arcs to represent links” [74].

Arc diagrams have been used to visualize weighted graphs, in which the strength of a connections is encoded as arc thickness (e.g. to represent common terms in text documents [36], or hotel guests [195]). In the PivotGraph technique, thickness represents the number of aggregated edges [194], which, in the special case of a one-dimensional layout, is equivalent to an arc diagram. The last visualization only displays one arc per node, and thus has no crossings, while the first two display multiple connections as transparent arcs on top of each other. Some Circos variant displays weighted links between circle segments as ribbons with varying thickness, with the ribbons spread out on the circle segments [112]. Conceptually, our approach is relatively similar, yet our approach is linear instead of circular, and seems more suitable for sequential datasets.

5.4 Sankey Arcs

Our Sankey Arc technique displays all weighted edges of a node adjacent to each other. The development was based on the need to visually adjust nodes with similar vertex strength, and to overcome occlusion of arcs at the node base. The intention of this technique is to reduce visual clutter in comparison with classic arc diagrams.

The design of Sankey Arcs was guided by the following goals:

1. Display node strength independent of edge distribution.
2. Enable comparison of in-weight and out-weight.
3. Emphasize the total weight of a node.

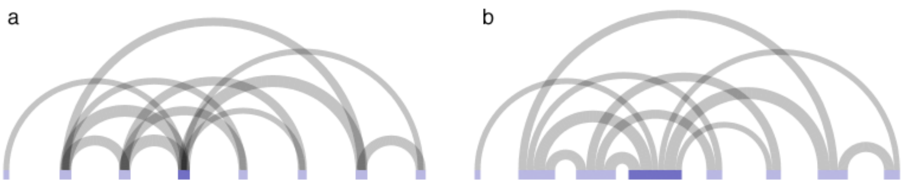


Figure 5.2: Two nodes with same vertex strength in a) a classic arc, and in b) a Sankey Arc diagram.

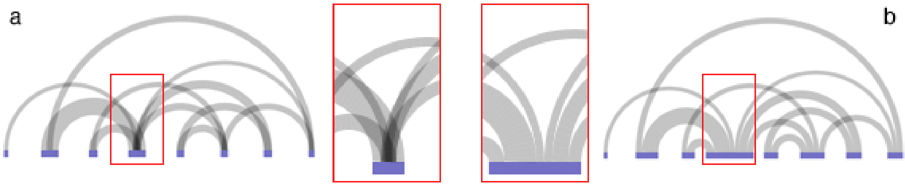


Figure 5.3: Transparency vs spread out.

By spreading out the imposts (i.e. arc bases), all edge weights of a node become visible. In Figure 5.2b a node with many thin arcs is visually comparable to another node having few strong connections. In a diagram with overlapping arcs Figure 5.2a this is concealed.

The volume of stacked transparent arcs also obscure the in-weights and out-weights (Figure 5.3a). Bundling the incoming and outgoing arcs helps understanding at a glance which direction has more weight (Figure 5.3b). Furthermore, by showing each edge weight in parallel, the total weight is integrated into the arcs. Oppose to some disjoint glyph, this displays the value in a unified manner (with the cost of using more space).

Besides enabling to visually compare nodes and edges, arc diagrams support understanding the relation between weight and distance (as the angle of the arc hints to the distance), and the distribution of amounts (e.g. if there are clusters of connected nodes). These two features already exist in classic arc diagrams, but are more profoundly visually highlighted in Sankey Arcs.

5.4.1 Algorithm

Figure 5.4: Same graph as a) unordered arc diagram, with b) spread out arcs, and c) reordered head and tail positions.

In order to minimize arc crossings, we propose the application of two additional rules: Firstly, all incoming arcs (i.e. arcs where the current node is the tail node) are placed on the side of their head nodes, and all outgoing arcs on the side of their tail nodes (Figure 5.4b). Secondly, the edges of a single node are ordered by distance towards their respective counter nodes (Figure 5.4c). That is, an incoming arc is placed the further towards the head node the closer that head node is (respectively, outgoing arcs towards tail nodes).

As the arc's start position is depending on all arcs at the head node, (and analogous its end position on all at the tail node), the algorithm has to iterate twice over all edges in order to incorporate the position and weight of every in-coming and outgoing edge.

The general algorithm to create Sankey Arcs is described as pseudo-code. Nodes are required to be sorted by their natural order (time, spatial distance, etc), or by some artificial order (e.g. alphabetical).

```
For each edge e
  e.head.outWeight += e.weight
  e.tail.inWeight += e.weight
  For both e.nodes n
    n.totalWeight += e.weight

Sort all edges by head and then by tail nodes

For each edge e
  // If e is edge of new head node
  If e.head != prevEdge.head
    headPos = e.head.pos + e.head.totalWeight / 2
  headPos -= e.weight
  // If e is first edge of tail node
  If tailPos in posList for e.tail
    tailPos = e.tail.pos + e.tail.totalWeight / 2 - e.tail.outWeight
  tailPos.x -= e.weight
  drawArc(headPos, tailPos, e.weight)
```

For simplicity the pseudo-code describes the algorithm for arcs from left to right. We also used the edge weights directly, while in implementations they should be encoded as thickness via some appropriate mapping method

5.4.2 Positioning nodes

In comparison to a classic weighted arc diagram (Figure 5.5a), the nodes in a Sankey Arc diagram tend to consume more space. This is due to the width nodes with more than one arc need to display the total weight of their connections. Thus, nodes might converge or overlap, and arcs of neighboring nodes might obstruct each other (Figure 5.5b). To resolve this, the design properties of the diagram need to be modified. We describe two possible methods.

- **Adapting the layout** algorithm to position the nodes. This can be achieved by either enlarging the distance between each node (e.g. using more than half the maximum width of the largest node) (Figure 5.5c), or by using a fixed gap between nodes. In both cases, the overall size of the diagram increases.
- **Modifying the visual encoding** for arc thickness. Applying a mapping method producing thinner arcs and nodes results in a total width equal to or smaller than the original (Figure 5.5d). In the example shown, the

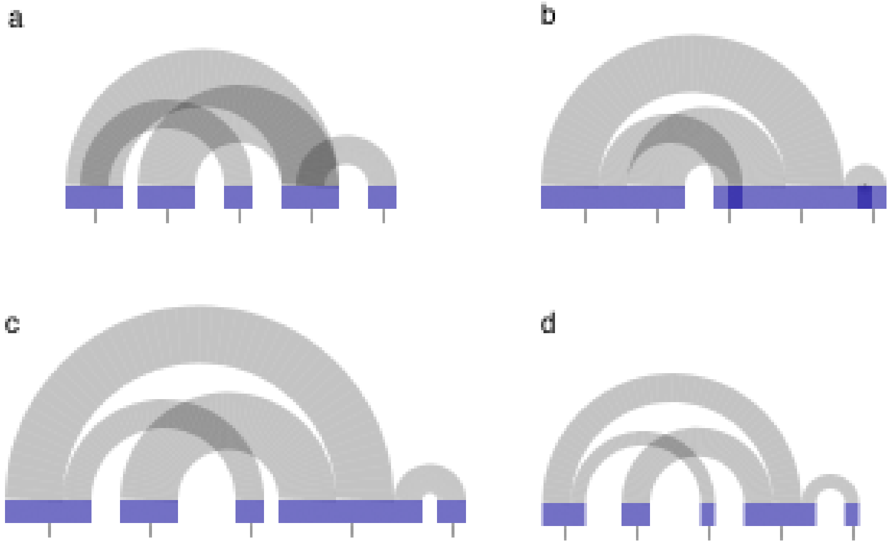


Figure 5.5: Graph shown as a) arc diagram, and as Sankey Arcs with b) overlapping nodes, c) larger distance between nodes, and d) reduced arc thickness.

adaptation was done in a way so that the same distance between nodes (as in Figure 5.5a) could be used.

Both are feasible solutions to prevent overlapping. The choice of which one to use depends on the size of the data set and the number and weights of the connections. Generally, we recommend to use a combination of both, starting with reducing the distance between the nodes, and – if that is not sufficient – adapting the visual encoding iteratively until the whole diagram fits into the designated space.

5.5 Limitation

In the classic technique all arcs start at the center of a node so that the height of an arc only depends on the distance between its nodes. Hence, a viewer comparing two arcs can directly deduce the distance equivalence or difference from the height (Figure 5.6a). In Sankey Arc diagrams the starting and ending positions of an arc rely on all other arcs of the same node. Thus, it not always encodes an equal distance to an equal height (Figure 5.6b).

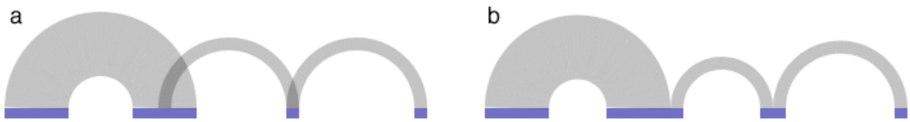


Figure 5.6: Comparison of a) an arc diagram with same heights, and b) a Sankey Arc with different heights.

Nodes of an arc diagram are positioned equidistantly in most cases. Often, arc diagrams are visualizing data sets with discrete order (such as website ranking [58], or text chapters [74]). Dörk et al. explicitly opted against a continuous timeline for their arc diagram even though the nodes are representing years, because of the non-uniform distribution of their data [45]. In theses cases, an exact comparison of height might not be necessary. This limitation affects arc diagrams where the precise distance is important, and is really relevant only for nodes with very high vertex strength.

5.6 Case study

As a proof of concept we applied the technique in a visualization for public transit ridership in Singapore (Figure 5.7). This was part of the LIVE Singapore project, which combines and disseminates various urban data sets to provide citizens visual and tangible access to information about their city [109].

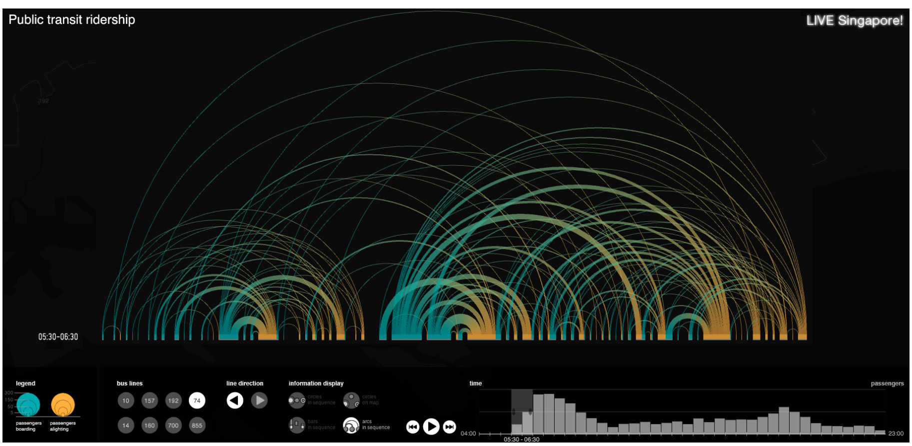


Figure 5.7: Ridership visualization with legend, bus lines and visualization controls, and an interactive time range slider.

In Singapore, a contact-less smart card is used to pay the distance-based fare. There is a strong incentive for passengers to not only tap in on boarding, but also to tap out when alighting, as otherwise the maximum fare has to be paid. This results in precise origin-destination paths for each ride.

The arc diagrams visualize boarding and exiting passengers at bus stops, and the rides taken in between. Each arc signifies passengers going from one station to another. The width of an arc represents the number of passengers. Users can switch between multiple bus lines, and interactively select a time range (see Figure 5.7), to compare for instance the morning with the evening rush hour.

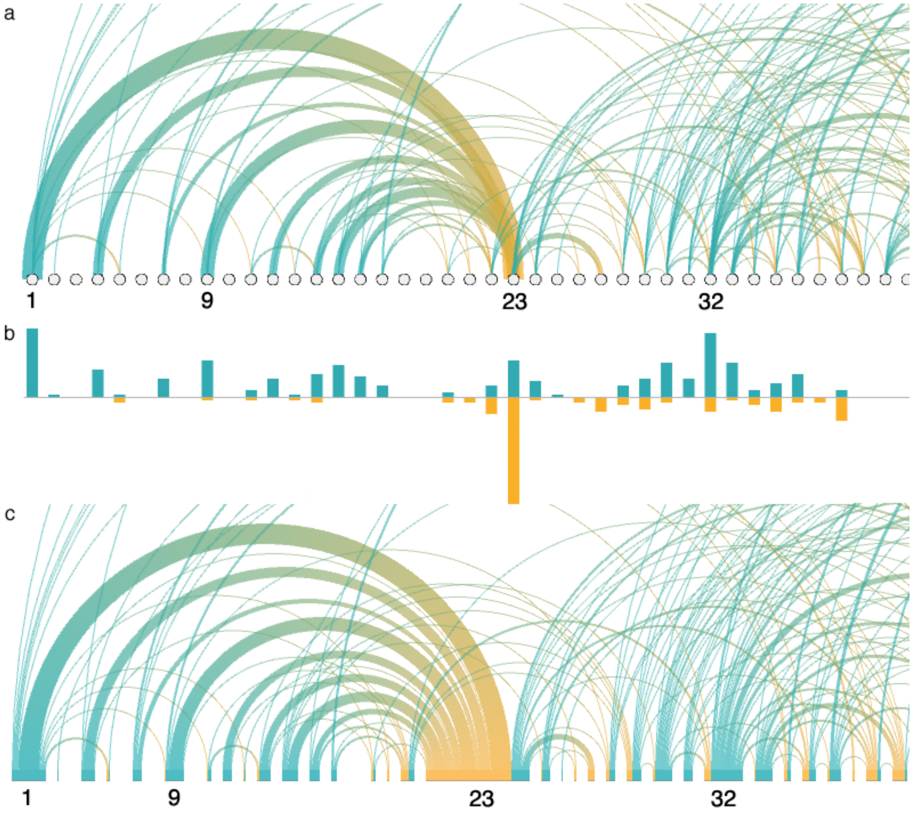


Figure 5.8: Rides between bus stops as classic arc diagram (top) and as Sankey Arc (bottom), with passengers as bar diagram (middle).

In Figure 5.8, the bus stops of (the Western part of) bus line 10 in Singapore are shown. The number of passengers are double encoded as arc transparency, so that the most taken bus rides are easily discernible. Now, bus stops which are public transit hubs become visible. Some hubs have few strong connections (e.g. 9), some have many weak ones (e.g. 32), some have a mix of both (e.g. 23).

The visualization properties used in Figure 5.8a over-emphasize strong connections. Figure 5.8b shows bar graphs for each bus stop, with the upper one representing boarding, and the lower one alighting passengers. As the bars show, bus stops 1 and 32 have similar quantities of boarding passengers. This becomes apparent only with the Sankey Arcs technique (Figure 5.8c).

The ride direction is represented as color gradient from turquoise (boarding) to orange (alighting). While the results of a user study by Holten and van Wijk [87] suggest to use tapered connections for direction, we could not apply a visual mapping with varying thickness as this was used for encoding the weight (cf [86]). Hence, we used the second best according to the original study, and chose a color schema with higher legibility for color-blind viewers [102].

5.7 Conclusions

The main contribution of this paper is a visualization technique to display edge weights of nodes in a path graph. We described how this extension of arc diagrams create less visual obstruction by spreading out arcs.

With the use case we have demonstrated that Sankey Arcs help comparing nodes and their edge weights. Applying the technique in a real world visualization helped us to validate the applicability, from displaying arc directionality with colors, applying it to a set of public transit data with vastly different properties, and testing the performance with a highly responsive implementation for an interactive time range slider.

Our hypothesis as set forth in this paper and that will need experimental verification is that Sankey Arcs outperform classic arc diagrams especially in cases where few strong connections represented by arc width visually overlap with many weaker connections leading to an overall decrease in readability of the diagram. We plan a user study to establish in quantitative terms which technique of arc diagrams performs better.

Chapter 6

Unfolding - A Library for Interactive Maps

This chapter was previously published as:

Nagel, T., Klerkx, J., Vande Moere, A., and Duval, E. **Unfolding – A Library for Interactive Maps**. In Proceedings of the International Conference on Human Factors in Computing and Informatics (SouthCHI), vol. 7946 of Lecture Notes in Computer Science. Springer, 2013, pp. 497–513.

My contribution:

Unfolding Maps is self-initiated research project. I am the project lead, and responsible for the concept and software architecture of the library. I am the main developer of the software, with support from students as well as other contributors. I designed and performed the user study. The publication was co-authored by me with support from the other co-authors.

Other publications related to this project:

Nagel, T., Heidmann, F., Duval, E., Klerkx, J., and Vande Moere, A. **Unfolding – A Simple Library for Interactive Maps and Geovisualizations in Processing.** In GeoViz Workshop (2013).

6.1 Abstract

Visualizing data with geo-spatial properties has become more important and prevalent due to the wide spread dissemination of devices, sensors, databases, and services with references to the physical world. Yet, with existing tools it is often difficult to create interactive geovisualizations tailored for a particular domain or a specific dataset. We present Unfolding, a library for interactive maps and data visualization. Unfolding provides an API for designers to quickly create and customize geo-visualizations. In this paper, we describe the design criteria, the development process, and the functionalities of Unfolding. We demonstrate its versatility in use through a collection of examples. Results from a user survey suggest programmers find the library easy to learn and to use.

6.2 Introduction

Until the extensive digitalization of geo-spatial data, cartographic products have been nearly exclusively created by cartographers, geographers, and scientists from other disciplines with a spatial context. Nowadays, interactive maps and geo-visualizations are prevalent on the internet, on navigation devices and smartphones, as well as on large-scale multitouch displays in exhibitions and public spaces. Similarly, interactive or animated maps are used increasingly to communicate facts or stories related to geo-spatial information in various application domains [78].

Areas are ranging from social networks to mobility patterns to data journalism to many more. For example, Dodge et al [44] argue that there is a "spatial turn" in social sciences, and that researchers are exploiting the geo-spatial components of large data to understand spatial relations and interactions. They describe interactive geographic visualization as an essential research tool. MoMA Design curator Antonelli sees visualization as one of the central design disciplines [6], and demonstrates current trends with eight examples of "highest quality of design", of which six use geo-spatial data visualized on maps. Moreover, there is an increase in the interest of the general public, among others due to the wide-spread use of location based apps for smartphones. Due to the recent 'creativity boom', in which "novel types of graphic [...] and interaction were being applied to new data and new scenarios" [46], different user groups should be encouraged to experiment in the geovisualization field.

But while interactive geovisualization is useful in a variety of domains, the tools that can be employed to generate the visualizations are either cumbersome to use, or lack the appropriate functionalities. There is an increasing need

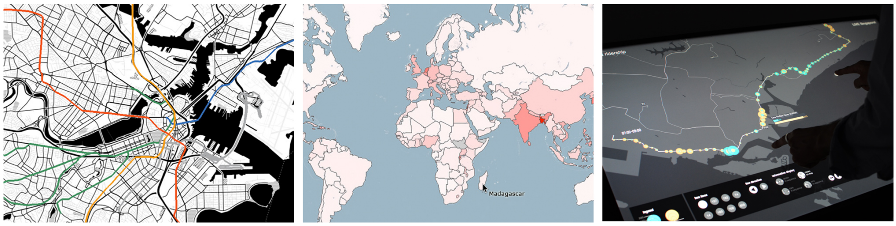


Figure 6.1: Three applications created with Unfolding: An animated map showing subways in Boston (left), an interactive choropleth map showing population density (middle), and a visualization showing ridership in Singapore for a multitouch tabletop (right)

for interactive maps and geovisualizations, and many amateurs and non-GIS researchers are now creating and customizing geo-spatial data representations. In order to support a democratization of tools and technology we developed the Unfolding library.

With our library we strive to support three different purposes, i.e. (i) having a simple API that is easy to learn and use, (ii) support creating prototypes to quickly visualize data and to rapidly test novel interaction techniques, and (iii) building applications for a broader audience. We chose to implement Unfolding as a Processing library, and are going to introduce Processing and explain our reasoning for choosing it in Section 6.5.3. Since its inception, Unfolding has been used in course assignments, research projects and commercial products. The iterative development of Unfolding was guided by the needs of, and with constant feedback from the library users.

The remainder of this paper is structured as following: We give an overview on related work (Section 6.3), and describe our design goals (Section 6.4). In Section 6.5 we introduce the Unfolding library, its interaction and visualization features, and our design rationales. We demonstrate its usefulness with exemplary applications for each of the three purposes, and summarize the results of a user survey in Section 6.6.

6.3 Related Work

In the following we examine software and tools for the creation of interactive geovisualizations. We describe their different goals, and how they are only partly fitting for the purposes we aim to support. We discuss their advantages and drawbacks, and describe how they differ from Unfolding.

6.3.1 GIS software

Standard geographic information systems (GIS) foremost aim is to support analyzing geospatial data, but often do not allow extensive adaptation and simplification for a non-GIS-experts audience. Researchers in the field of geovisual analytics have argued that software "should be lightweight, easily deployable and usable, rather than huge and complex like current GIS." [4]. There is the need for less complex software which encourages interactivity [200], and supports interactions facilitating a knowledge construction process [103].

Thanks to easier tools for creating customized maps since the release of Google Maps and other web mapping services there are more and more interactive maps created by persons who have no expertise in GIS. This kind of map mashups needs little or no programming to visualize information spatially [13]. While such mashups often only include dots on a map or other basic display techniques, the mashup principle of re-using existing technology has been described as a means to rapidly create prototypes for geovisualization [201]. Simpler web-based GIS applications support selected visualization (e.g. IndieMapper [94]) or interaction techniques (e.g. GeoCommons [61]), and customization to a certain degree.

Generalized, GIS software facilitates in-depth analytics, but is complex, has a high learning curve, and is intended for experts. Mashup tools are easy-to-use, suitable for quick data exploration, and intended for non-experts, but only allow employing a fixed set of techniques. An approach to fill this gap is the geoviz toolkit [72], which offers a graphical user interface (GUI) for users without programming expertise, yet it targets an audience of GIS experts.

Effective geo-visualizations employ established techniques, but tailor the visualization to the application domain and to the specific dataset. Thus, custom visualizations have to be created with toolkits or with software libraries.

6.3.2 Visualization and map libraries

The Java GIS library GeoTools provides extensive functionality for geospatial data, and aims to support developing complex spatial data processing applications [184], but is targeted to professional software developers.

In recent years, multiple libraries have been published with the intent to allow designers and web developers to create interactive visualizations. As we are not aware of surveys on modern visualization libraries aimed at these new user groups, we chose an online collection [42], of which 12 out of 43 tools include map or other geo-spatial components. Data visualization libraries such as d3

[23] or Prefuse [75] aim to supporting general purpose visualizations and include a broad spectrum of techniques. With this, however, they tend to not focus on the geospatial area.

Dedicated map libraries such as Leaflet [116] or Polymaps [154] offer functionality to create interactive maps, and display geo-spatial data. These libraries have proven value in practice, which is also why design and functionality of Unfolding were guided by them. However, they are intended exclusively for a web environment, and thus only partially support more advanced interactive applications such as exhibits for large multitouch devices. Furthermore, they are not developed for the Processing environment, which prevents the usage in existing Processing projects, and reduces the applicability for less advanced users (see Section 6.5.3).

We are aware of three libraries providing basic map functionality for Processing. Their purpose is to provide rudimentary mapping features: all of them offer the display of a geo-referenced map, with conversion methods between geo-locations and Cartesian screen coordinates and vice versa. The geomap library by giCentre [62] provides functionality to load and display Shapefiles, a standard file format for GIS data. It allows interactive feature picking, and color coding, e.g. for choropleth maps (a thematic map with its areas shaded according to a data value). Google Mapper [64] allows downloading a Google map section and storing it as single image. Unlike Unfolding, none of these Processing libraries provide zooming and panning, multiple coordinates map views, or other more advanced features. Lastly, ModestMaps [132] is an extensive map and geovisualization JavaScript library for the web, for which a port to Processing was created in 2008. The main JavaScript library has many of the features missing in the other Processing map libraries, but the port for Processing is not actively developed, and only supports some of the basics. However, the tile-handling mechanism was mature and feature rich, which we therefore used as basis for Unfolding's own tile-handling functionality.

6.4 Design Goals

This section introduces the design goals of Unfolding, and how the library enables developers[1] (i) to easily create simple sketches[2] with interactive maps, (ii) to quickly implement prototypes, and (iii) to create sophisticated visualizations, or even extend Unfolding's functionality.

[1] This paper differentiates between *developers* or *library users* for Unfolding library developers, and *end users* for persons using applications created with Unfolding.

[2] This paper uses the term *sketch* as introduced by Reas and Fry [158] where small programs act as software sketchbook allowing to quickly explore different ideas.

For these purposes, Unfolding was developed with the main goals of learnability, simplicity, and extensibility. To support the first goal, the library comes with extensive documentation, mostly in the form of tutorials and example code. The documentation can be found both online at http://unfoldingmaps.org as well as in the downloadable distribution. The library uses a simple programming interface (API) to support the second goal. Library users can create interactive maps in very few lines of code (see Code sample 1). And thirdly, the library provides reusable components, and employs a software architecture allowing to extend its functionality in order to create advanced visualizations.

6.4.1 Task areas

We identified design goals and requirements, based on the experience from our own design projects, from our teaching, and collected as feedback from external users of the library, and grouped them into three main task areas. These groups partially converge, and are not necessarily strictly disjoint, but are useful nonetheless to refer back to and to describe how we aim to support the dominant tasks of the target audience. We describe the activities, user groups, and typical use cases.

i **Learning** Includes all activities in which developers learn how to display geo-spatial data. Users in this group mostly create simple sketches where they show markers on an interactive map. They use it for experiments and small projects.

ii **Prototyping** Includes all activities in which library users explore and understand geo-spatial data in an iterative data visualization design process. This also includes to quickly prototype sketches to try out new visualization or interaction ideas. Developers include both beginners and advanced users.

iii **Creating** Includes all activities in which library users create larger projects. This can be for design studies by researchers to be able to evaluate novel techniques. This also can be for commercial or art projects where developers create complex geovisualizations.

All library users – that is persons creating visualizations or interactive applications with Unfolding – must have programming skills, ranging from beginner (learning) to intermediate and expert level (prototyping and creating). All of them have in common, that they not necessarily have expert geography or cartography knowledge.

Overall, Unfolding is developed to have a gentle learning curve, i.e. empowering to create standard visualizations in a few lines of code, and to create more complex visualizations when users are accustomed and more experienced with the library.

6.4.2 Design process of Unfolding

Since the first version of Unfolding in 2008, we continuously gathered feedback from library users. In the process of designing Unfolding its functionality was based on the lessons learnt from class room usage, and on the requirements of our own case studies in visualization. We follow the argument of Heer et al [75], and see iterative development, an established method for designing HCI, to be also a valuable design process for software libraries. In this vein, we discuss how the utilization of Unfolding in each task group helped the progress of Unfolding, and how the feedback from developers with different expertise levels helped us to balance learnability and functionality.

Learning. Since 2009 Unfolding has been used in six courses at Fachhochschule Potsdam, and two at IUAV University of Venice by the authors. Besides, it has been endorsed in various courses at international universities (e.g. Carnegie Mellon, ITP, MIT), with departments ranging from interaction design to computer science to urban studies. The use in courses and workshops for teaching basics on geospatial data visualization allowed us to observe how beginners were using the library, and simplify the API and improve the documentation.

Prototyping. In early stages of designing an application, quick visual representations of geo-spatial data help to understand them. While these data loading and visualization methods can be implemented with other software or libraries, Unfolding provides them too in order to support library users all the way from learning up to creating. In addition, users have employed Unfolding to create geovisualizations with the purpose to prototype and evaluate new techniques. Unfolding aims to bridge the gap between traditional and novel visualizations by easing the creation of rapid design experiments.

Creating. Comments and suggestions from advanced users employing Unfolding in research, design, and commercial projects helped us refine existing and add frequently demanded features. Furthermore, successful design projects can act as flagship and inspire new groups of users.

6.5 The Unfolding library

The features of our map library include zooming and panning, multi-touch functionality, dynamic map tile handling, an event system, multiple coordinates map views, standard and custom markers, loading of various geo data formats, and more. This section describes selected basic interactions and visualizations methods, demonstrate its features and usage by examples, and explains our design rationales.

The code samples in 6.5.1 are to demonstrate the usage of the library in order to implement some of the fundamental functionality. This is to show how the basics are achievable in just a few lines of code, as stated in one of our design goals. For longer code examples we deem a paper not as the most appropriate form, and refer to the example section on our web page.

6.5.1 Interaction & Visualization

Unfolding supports basic techniques for interactive maps such as zoom and pan, but also other common but slightly more advanced techniques such as Overview+Detail, i.e. showing a large scale map view while keeping the context by displaying the selected region on a large scale map.

Basic map.

In just three lines of code library users can create an interactive map. The map is displayed in a default style with cartographic data from OpenStreetMap [71] and tiles from CloudMade [39].

```
UnfoldingMap map = new UnfoldingMap(this);
MapUtils.createDefaultEventDispatcher(this, map);
map.draw();
```

Code sample 1. Creating an interactive map in Unfolding

To use another map style, developers can specify a different provider as second parameter when creating an UnfoldingMap. Our library provides eight preconfigured map tile providers for educational purposes. Developers can also create their own map provider to use customized map styles adapted to the requirements of their visualization. For instance, if the objective of the map is to support general spatial recognition while being discreet enough to not hinder the display of the data and interface layers, a minimal style with selected geographical features could be employed.

Basic interactions.

By creating the default event dispatcher (as shown above), end users already can interact with the map. They can pan the map by dragging it with the mouse, or by using the arrow keys on the keyboard. Using the mouse wheel zooms in or out, which also works by pressing + or - keys. Double-clicking on the map centers it around that location, and zooms in one level. These basic interaction patterns were based on studies for map interactions ([73], [203]) and well-established design patterns for navigating and browsing [179].

Basic interactions with markers, i.e. visual representations of geographic features or data entries, are also provided out of the box. These include selecting and highlighting markers by clicking or tapping on them. More sophisticated interactions such as brushing and linking have to be implemented by the developers, but can employ Unfolding's event mechanism.

Multitouch interactions.

Unfolding also provides interaction handling for multitouch devices. To turn on this feature developers have to register Unfolding's multitouch handler, which maps gesture input to map manipulation methods.

We focused on simple navigation patterns (e.g. pinch to zoom, drag to pan, tap to select) to support end users interact with the maps in ways more laymen have experience with, due to the wide-spread dissemination of smartphones and tablet computers with multitouch capabilities.

Visualizing data on a large-scale multi-touch surface allows the application of natural interaction techniques to engage a broad audience. Unfolding supports a high fluidity of the visualizations, with smooth transitions and low responsive times, in order to create enjoyable user experiences. See the project descriptions in Section 6.5.2 for examples of visualizations on multitouch tables.

Visualization features.

Developers can use Unfolding's built-in marker mechanism to display geo-spatial data on the map. When end users interactively change the map area, or when the map is animated, latitude and longitude of the locations are converted to the correct screen positions, in the background.

```
Location berlinLocation = new Location(52.5, 13.4)
```

```
Marker berlinMarker = new SimplePointMarker(berlinLocation);
map.addMarker(berlinMarker);
```

Code sample 2. Adding a location marker to display

Unfolding provides a default marker style, and has point, line, and polygon markers out of the box. Besides these markers, developers can also create multiple markers consisting of two or more markers of any kind, or use various connections representing some relationship between markers.

```
UnfoldingMap map;
void setup() {
  map = new UnfoldingMap(this);
  MapUtils.createDefaultEventDispatcher(this, map);
  List features = GeoRSSReader.loadData(this, "quakes.xml");
  map.addMarkers(MapUtils.createSimpleMarkers(features));
}
void draw() {
  map.draw();
}
```

Code sample 3. A Processing sketch loading and displaying earthquakes on an interactive map. The earthquake data comes from the U.S. Geological Survey institution provided in the GeoRSS format

The library also allows reading standard formats for geospatial data, and automatically creating the respective graphical representations. The provided data readers support basic functionality, and do not fully implement the respective specifications. The GeoJSON parser supports most features, while the GeoRSS reader supports only Simple and W3C Geo, but not GML, and the GPX reader only enables reading track points. The aim was not to re-implement functionality developers can use and integrate from more sophisticated GIS libraries, but to enable getting quick results in a rapid prototyping approach. By building upon the Processing framework, developers can easily create own data readers. For example, Fig. 6.1(left) shows the display of subway lines in Boston, in which the geospatial routes as well as the train schedules comes from General Transit Feed Specification (GTFS) files provided by the transport authority.

The marker style can be customized, or completely implemented anew by the designers. The second option allows using data glyphs such as donut charts or any other data display technique (see Fig. 6.3). By mapping a value to the brightness value of a polygon marker, one can create simple choropleth maps. The example in Fig. 6.1(middle) shows an interactive version displaying population density of the world. End users can select single countries by hovering over (one of) the country's polygons, and additional data is display on demand.

6.5.2 Example projects

The following two Unfolding projects were selected to represent the spectrum of how the library can be used, and to exemplify various advanced features of Unfolding.

Figure 6.2: Visualization of research networks on a multitouch table (left) with two Unfolding maps showing institutions (clipping right)

Max-Planck-Research Networks.

A visualization of research networks on a multitouch table [177]. It uses three coordinated multiple views: one showing a network with institutions and their connections based on co-published papers, and two maps showing the locations of institutions in Germany and the world (see Fig. 6.2). Tapping on an institution in any view highlights it in all other views. The maps are implemented with Unfolding, and use custom styled map tiles. The application uses Unfolding's multitouch capabilities in order to allow end users to slide for panning and to pinch for zooming the maps. Brushing and linking interactions can be developed with Unfolding's event system to coordinate multiple maps.

Figure 6.3: Visualization of public transit ridership in Singapore, using Unfolding's built-in multitouch interactions for map manipulations

Live Singapore.

A visualization of public transit ridership in Singapore [131]. It shows bus passenger flows in three coordinated visualizations (map, time chart, arc diagram), and allows users to interactively explore bus lines and areas of interest (see Fig. 6.3). Unfolding was used for the map view and for the display of the geo-spatial data glyphs. Interactions with the map are restricted to the city state of Singapore, i.e. when an end user pans or zooms outside of that area, the map gently animates back. One of the challenges in developing this visualization was to create a performant data display method in order to keep high responsiveness on every user interaction. End users can slide through the time dynamically which is directly reflected in the geo-spatial markers. Unfolding supports traversing the visualization pipeline in an efficient way, so that after users adapt the time range the data gets newly aggregated and displayed nearly instantaneously.

6.5.3 Design rationale

In this section we explain the reasoning for our design decisions in developing Unfolding.

Simplified Java dialect.

Processing is a programming language to create interactive graphics, which is used for learning, prototyping, and production [158], and "targets an audience of computer-savvy individuals who are interested in creating interactive and visual work through writing software but have little or no prior experience" [159]. It has a large and active community, with many libraries providing particular additional functionality if needed. Furthermore, Processing is beneficial for more advanced developers: in comparison to visualization libraries which often use high level programming languages, and an elaborate component structure, Processing provides a low level graphic based environment. The flexibility to investigate and develop new visualization and interaction techniques usually requires relatively low level programming and considerable development time [201]. With Unfolding we aim to support this flexibility while reducing the complexity.

One drawback for more advanced developers is the very simple editor (due to the aim of not overwhelming beginners), with nearly no features of modern Integrated Development Environments (IDE), such as code assistance. To circumvent this, Unfolding provides its library for Processing, as well as for full Java IDEs such as Eclipse.

Tile-based.

Users know and expect the interaction possibilities of online maps. Tile-based maps are a established way of providing zoom and pan functionality. It furthermore enables to select from a huge range of existing map styles, or customize styles with existing tools. The library uses the so-called Slippy Map technique [71], which uses a tile-based algorithm with pre-rendered map tiles for fixed geographical locations in different provided zoom levels. This is used widely for online web map services (e.g. Google Maps), and custom map styling applications (such as CloudMade [39], TileMill [126]). While map tiles technically support other tile sizes or other map projections, typically the same size of 256x256px, and the same Spherical Mercator projection is used. This restricts geovisualizations to a subset, but simplifies the handling. By using such tiles, non-GIS-experts can easily use existing web tiles or custom map styles, and not care about an own map server stack.

Desktop-based.

For creating sophisticated geovisualization applications, i.e. for big sets of data, or creating multitouch interactions for exhibitions, the use of the Java based programming language Processing includes the ability to use OpenGL for high performance visualizations of tens of thousands of visual elements. While web technology such as WebGL more and more includes these abilities, it still needs more advanced programming skills, and extensive knowledge of the newest browser developments at the moment. Another reason for using a desktop based programming language is the ability to employ large-scale interfaces, such as visualizations on interactive multitouch tabletops.

Simple software architecture.

While one of the principles of Processing and many Processing libraries is to provide most methods in a single class for easier access, this comes with a cost: the API itself becomes unstructured and bloated, and the functionality more complex to extend. Similarly, visualization libraries offer lots of functionality, and while they can be extended it tends to be difficult. This is due to the complex software architecture, where new components need to adhere to the sophisticated class structure. The advantage is that – after learning the deeper parts of the API and implementing new features correctly – an integrated component can profit from existing mechanisms, e.g. interaction or transition patterns. In Unfolding, we intended combining the simplicity of Processing with proven design patterns in software architecture to achieve the extensibility of other libraries. One of our aims was to create a clear Unfolding API enabling beginners to create own sketches showing geo-spatial data, while at the same time allowing more advanced developers to enhance functionality in a reusable way.

Documentation.

To support good learnability, the library comes with extensive documentation, mostly in the form of tutorials and example code. The basic API documentation comes in standard JavaDoc format, and describes the methods of Unfolding. We followed Robillard [163], who proposed to use examples, and categorized them in snippets (short code examples), tutorials (code examples with prose), and applications (longer code examples from actual applications). We distribute various examples in the Unfolding library. On the website we additionally publish tutorials and example applications, so beginners can use or copy these code samples directly in their sketches.

6.5.4 Summary

In summary, Unfolding provides functionality to handle geo-spatial data and display them on interactive tile-based maps by using reusable components in Processing. Unfolding is not just a collection of existing visualizations; it provides the foundation to create interactive maps, and a basic set of reusable components for building customized or novel geovisualizations.

6.6 Evaluation

In this section we demonstrate the usefulness of Unfolding by presenting selected projects, and describing our user survey and its results. We also give some numbers indicating the library's acceptance.

6.6.1 Applications

We follow the argument of the authors of the widespread Protovis visualization library that one of the main values of a toolkit is in the design and dissemination of successful visualizations [22]. We collected 40 projects which were publicly accessible on the web and referred to the Unfolding website, or were described in publications. From these, we selected notably successful projects as examples for each of the three task groups.

Learning. Student projects have won student competitions (Tweetography [151] is the Winner of the Harvard Conant Prize for "Best Non-Traditional Project", and Foreign Domestics [55] is one of the winners of the Visualizing Marathon 2012), or have been featured in design magazines (LiquiData [57] in Weave magazine [107]).

Prototyping. An example of using Unfolding as a prototyping tool to quickly analyze data-sets is an animation of viewers of TED talks [127]. Various research projects have employed Unfolding to create interactive prototypes to be able to develop and evaluate novel visualization and interaction methods (e.g. [140], [139]). In a visualization for exploring geo-spatial networks a new interaction technique for solving the fat-finger problem was introduced. Their user study showed that end users could casually interact with the system and were satisfied with the ease of use of this multitouch visualization [139].

Creating. In the last group, successful design projects were publicly exhibited (e.g. Max-Planck-Research Networks [177], a visualization of research networks on a multitouch table, or The Quiet Walk, a system for sonic exploration of urban space [2]). A commercial project for visually analyzing tax-free sales on an airport [182] has been featured in Cairo's book on visualization [29].

Overall, we believe these Unfolding applications demonstrate compelling real-world usage.

6.6.2 Dissemination

Unfolding was publicly released in August 2011, and the first public version (0.8) was downloaded over 3000 times in the following twelve months. The next version (0.9) was published end of September 2012 and downloaded over 2200 times in the first three months (as per 31st December 2012). While these numbers are just a single measurement, it indicates that Unfolding is widely used, and well accepted. (For instance, the authors of the Prefuse library mention in [75] it had been downloaded 1300 times after the alpha-release.)

6.6.3 User survey

We ran a user study as an online survey after the design and implementation of the second release of Unfolding. The purpose of the survey was to gather feedback on library and feature usage, and measure satisfaction on several aspects such as learnability and suitability. A secondary intention was to gather feedback in order to further improve Unfolding.

Survey design.

The questionnaire consisted of sections on the participant's background and prior experience, on the projects they used Unfolding for, and on their satisfaction with the library's features and use.

The survey is partly based on an ISO standard to evaluate software quality [100], and partly on the System Usability Scale (SUS) to collect the subjective rating of the library's usability [27]. We adapted the phrasing in order to have precise yet not overly formal questions. The drawback is that we did not adhere to the standard, and would not be able to compare our results with the usability of other systems. As we have not found other studies on visualization libraries using SUS, we deemed this as acceptable. We mainly tried to keep the survey form brief. We encouraged participants to give comments and constructive criticism, by providing free-form text fields with open questions (e.g. “Do you have any suggestions on how to improve Unfolding?”). All these aspects were based on recommendations to increase response rate in online surveys [146].

We used a 5-point Likert scale for satisfaction (ranging from “Highly satisfied” to “Not at all satisfied”), and for agreement to given statements (ranging from “Strongly agree” to “Strongly disagree”). Overall, the survey contained 12 multiple choice, 7 Likert-scale grid, and 6 open questions. Test participants from our group needed circa 15 minutes to fill out the complete form.

The survey was designed as an online questionnaire, was accessible under a public URL, and ran for 10 days in early December 2012. All responses were anonymous.

Participants.

As our intention was to gather feedback from persons familiar with Unfolding, we chose library users as potential participants. These persons identified themselves by being active in the Unfolding community, be it on the forum, having published their Unfolding projects online, or having contacted us with questions before. We invited 93 persons via e-mail, from which 32 participated (34% response rate). This of course means we did not collect feedback from developers who decided against Unfolding, which might have biased the satisfaction results. However, we announced the survey on the Unfolding website and in the Processing community forum, via which we received another 5 responses. Overall, this resulted in a total of 37 survey submissions.

Participants were from all age groups (16% under 24, 44% 25-34, 31% 35-44, 9% over 45 years), and nearly half of them students (41%). They stated their expertise mainly in Design (21 participants) and Visualization (18 p.), with Software Development (15 p.), Data (10 p.) and GIS (2 p.) as runner-ups (participants could enter more than one area). They self-assessed their skill level mostly not as novices, with 25% expert, 41% advanced, 25% intermediate, and 9% beginner skills.

Survey Results.

In the following, we present how satisfied participants were with Unfolding's usability and features, and discuss some further results.

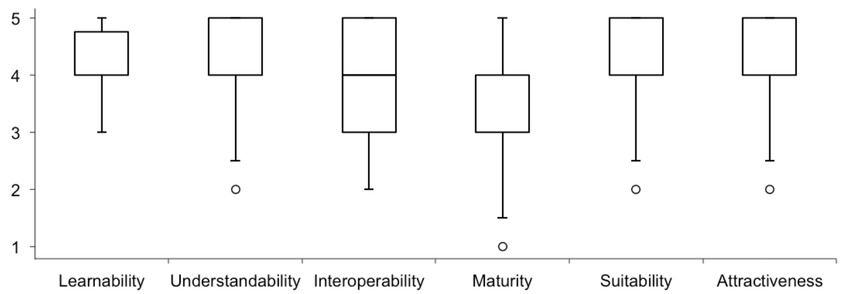


Figure 6.4: Satisfaction with Unfolding

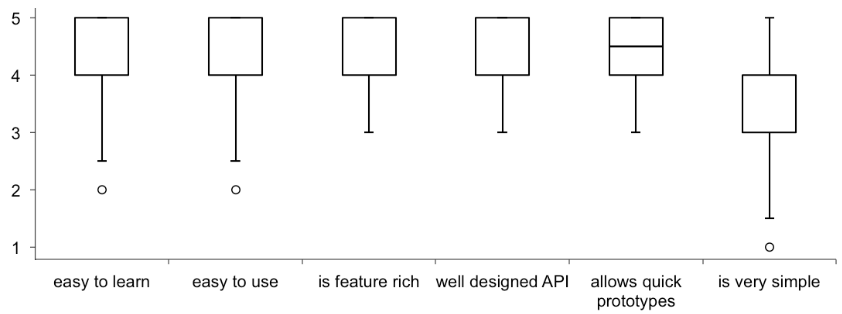


Figure 6.5: Agreement with statements

Participants were mostly highly satisfied or satisfied with Unfolding's learnability, understandability, and suitability (see box plots in Fig. 6.4). They also agreed to the statements that Unfolding is feature rich, and has a well designed API (Fig. 6.5).

Nearly all participants were highly satisfied or satisfied with Unfolding's basic features (such as displaying maps (97%), or enabling zoom and pan interaction (91%)). However, fewer participants were satisfied with more advanced functionality such as displaying labels (51%) or loading geo-spatial data (54%). While these numbers still indicate a majority of users being satisfied, we assume a connection to the documentation of these more advanced features.

Most participants were highly satisfied or satisfied with examples (62%) and tutorials (53%). This reflects our decision of focusing on these sections for learning Unfolding (cf 6.5.3). However, participants were not fully satisfied with the API documentation (38% highly satisfied or satisfied). This suggests that even though studies have shown developers use examples and tutorials to learn a new API, and re-use existing code snippets to quickly create own prototypes [163], library users expect a complete and well-written interface description, in any case. Three participants suggested improving the documentation in our general free-form comment field.

More than half the participants had some prior experience with GIS software (19% use it often, 19% occasionally, and 22% at least once). Besides the Google Maps API (57%) few have used other map libraries often or occasionally (9% Leaflet, 12% Open Layers, 12% PolyMaps, 15% ModestMaps). However, around one third or more have used these libraries at least once (28% L, 40% OL, 31% PM, 46% MM, respectively). To the question why Unfolding was chosen over other libraries, free-form responses included the Processing environment (e.g. “well integrated with Processing”), and the ability for quick prototyping (e.g. “it’s quite easy to get results quickly”, “It allowed me to dump geo data directly on a map in less than an hour”). Three participants named the integration with TileMill as reason. We did not expect the latter, as other libraries also allow this. We assume this is due to a tutorial about Unfolding’s TileMill functionality which was linked on well-known visualization blogs.

Participants used Unfolding for visualizations ranging from student to research to commercial projects. They achieved what they planned (81% agreed or strongly agreed), and found Unfolding to be helpful in doing so (87%).

Overall, participants were highly satisfied (53%) or satisfied (38%) with the library. Most participants (88%) plan to use Unfolding in the future (with 6% not, and the rest don’t know).

6.7 Conclusion

We presented the Unfolding library to create interactive maps and geovisualizations. Both creating our own applications, as well as collecting feedback from visualization projects by others has helped us to adapt the library, and to repeatedly refine its function range. The results from our user survey prove that Unfolding achieved our design goals. Most participants were highly satisfied or satisfied with our library. We see the use in various courses, in student, research and commercial projects as further indicator for the learnability and usability of the library.

Overall, we have shown that Unfolding is beneficial for learning, prototyping, and creating interactive maps and geovisualizations.

6.8 Acknowledgments

We like to thank Felix Lange, and all other library contributors. We also thank the users of Unfolding, especially students from FH Potsdam and from IUAV University of Venice for their feedback, and the participants of the survey. And we like to thank the anonymous reviewers for their helpful feedback.

Chapter 7

Conclusion

7.1 Thesis summary

In the first chapter, we motivated our research by introducing the current state of geovisualization for casual exploration, and the challenges therein. We identified the research questions, described their scope, and elaborated on the related research fields. In chapters 2–4, we introduced three case studies in separate yet related domains, described the objectives and design of our prototypes, and reported on the outcomes and research contributions. Prompted by the recurring issue of visualizing relations we then described a novel technique in Chapter 5. Based on design objectives of the case studies, and the recurring task of constructing interactive geovisualizations, we developed a software library. We described its user groups, its design goals, and its contributions in Chapter 6.

In the following section, we are summarizing our contributions with the case studies, classify used techniques and technologies, and discuss some general lessons learnt in regard to geovisualizations for casual use (RQ1). We then discuss our contributions in regard to the specific challenge of visualizing relations between geo-referenced data (RQ2), as well as in regard to our support of visualization construction with a software library (RQ3). We conclude with a critical reflection of our research approach, a discussion of future perspectives in regards to follow-up work, and close with the final remarks of this dissertation.

7.2 Visualizing tempospatial data (RQ1)

In this section, we discuss our research in regard to RQ1, report on the specific contributions of each case study (Section 7.2.1), on the used techniques therein (7.2.2), discuss our lessons learnt in visualizing tempo-spatial data for casual use (7.2.3), and summarize our contributions in Section 7.2.4.

7.2.1 Summary

We briefly summarize for each case study how they visualized multivariate tempospatial data for casual exploration, and highlight the achievements and contributions.

Case Study 1: Venice Unfolding

With Venice Unfolding we designed and evaluated a visualization of urban redevelopment projects, providing tangible interactions to support faceted browsing of architectural metadata. It was aimed to bring together citizens and urban planners to explore multi-variate data within the Venetian redevelopment process.

- Reduced the barrier between the physical world and virtual data.
- Eased the understanding of faceted geographical data.
- Enabled filter and selection of taxonomy categories and values.

The main contribution was the design and evaluation of a novel interaction method consisting of a polyhedron people can tilt to filter and search through the taxonomy, place on the tabletop to select specific projects, and rotate to browse through a project's background information. This facilitated interactive exploration of faceted data for casual use without providing complex user interfaces (RQ1.1).

Case Study 2: Muse

With Muse we designed and evaluated a tabletop visualization of collaborations between research institutions. It has been demonstrated in-situ at two conferences, and evaluated with conference attendees. Based on the design decisions of the multi-prototype iterative design process, we described best-practices and guidelines for geovisualizations for casual use.

- Acquired and mined affiliations from publication data based on criteria from expert interviews.
- Supported revealing collaborations between institutions through interactive visualization.
- Developed and demonstrated in a multi-prototype iterative design process.

One major contribution lies in the exhibition of the prototypes at scientific conferences, where they engaged researchers and other conference attendees to explore their personal network, as well as to act as casual background to initiate discussion on future collaboration (RQ1.2).

Case Study 3: Touching Transport

With Touching Transport we designed and evaluated a multitouch visualization of public transit network. It supports the exploration and understanding of complex tempo-spatial data for experts and non-experts. We explained why we used an unusual design process with in-the-wild observations informing a lab study.

- Supported revealing patterns and trends of public transport through visualization.
- Investigated how our system supports gathering insights for three different user groups.
- Provided three views, unified by style and transitions instead of multiple coordination.

One of the main contribution was the design of this tabletop visualization system with multiple perspectives into a complex tempo-spatial data set (RQ1.3). Furthermore, we demonstrated that our system empowered users with varying levels of previous knowledge gaining new insights, while attracting casual users with an appealing style.

Summary

While only the latter two were actually on display at the targeted location, all case studies were intended to be exhibited in semi-public settings for casual use: at the visitor area of an urban development center, to venues of scientific conferences, to museums and exhibition areas. We examined how to design interactive geovisualization systems in such ways to incite curiosity and attract non-expert users so they approach the system, explore the visualized data, and ultimately gain insights into the presented domain.

- Designed attractive and effective visualizations.
- Developed high responsive system with instantaneous data aggregation and filtering (thanks to Unfolding software architecture).
- Inferred design lessons for constructing aesthetic and usable visualizations for casual exploration.

All three case studies offered visualizations of personally relevant information to people in both everyday work and non-work situations. As an ideal example for complex time-varying geo-referenced data where non-experts have an interest in we focus on our third case study. Citizens who may or may not use public transport can explore their neighborhood, or their commuting paths. An important aspect of urban mobility is its tempo-spatial component, thus a visual exploration tool needs to employ geographic and temporal visualizations. As interactive geovisualization can support users to find patterns, relations and trends in public transit data [53], our goal was to select and adapt appropriate visualization methods for public transit data to be explored in a casual setting. However, some of the findings from a case study can be generalized. In the next section, we are describing used visualization and interaction techniques in order to be able to discuss implications and guidelines for casual tempo-spatial data exploration in general.

7.2.2 Classification

We describe and classify the objectives and domains of the three case studies, the used data, the visualization and interaction techniques, the tabletop hardware, as well as the utilized evaluation methods in Appendix Section A.1. The taxonomy is based on [38], and adapted to our requirements and case study specifics. Below, you can find Table 7.1 for an overview.

			Venice Unfolding	Muse			Touching Transport					Foreign Domestics	A day in Berlin	1 Year of Biking	Shanghai Metro Flow	Bumping Borders
				Muse 0	Muse 1	Muse 2	General	Map	Time-Series	Arcs						
Data	Spatial	Points	x	x	x	x		x				x	x		x	x
		Lines / Paths						x					x	x	x	x
		Areas		x	x							x				x
	Spatial Scale	Single place	x					x								
		Neighborhoods	x					x					x		x	
		City / Region	x		x	x		x	x	x			x	x	x	x
		Country		x	x	x						x				x
		World		x	x	x						x				
	Temporal	Points	x				x						x		x	x
		Interval		x	x	x	x					x	x	x		
Visualization	Map	Map (simple areas)		x												
		Map with details	x		x	x		x				x	x	x	x	x
		Choropleth map		x												
	Geographic position	Symbols	x									x	x		x	
		Graduated symbols	x	x	x	x		x								x
		Bivariate glyphs						x	x	x						
	Relations	Connections	x		x			x	x							
		Connections with attribute	x							x		x	x		x	
		Weighted connections				x				x						
	Metadata	Tooltip with text	x					x	x							x
		Tooltip with graphs		x				x	x							x
		Tooltip with media	x													
		Detail area		x												x
	Graphs	Bars		x	x				x							
		Histogram		x			x									
		Radial time-series		x												
		Node-Link diagram						x				x	x		x	
	Other	Small multiples							x			x			x	
		Time-series		x					x						x	
		CMV		x	x	x	x									x
Interactions	Map	Slide to pan	x		x	x		x					x			x
		Pinch to zoom	x		x	x		x					x			x
		Rotate to re-orient	x		x	x										
		Tap on object to fit		x				x				x				x
	Select item	Tap/click marker	x		x	x		x	x	x			x			x
		Tap cluster				x						x				
		Tap country area		x	x											
		Tap on button											x			x
		Tap on connection				x							x			
	Time	Static										x			x	
		Animation														x
		Start/stop animation					x						x		x	
		Select time	x	x	x		x									
		Select time range					x									
	Filter category	Tangible rotation	x													
		Menu: Direct	x					x								
		Menu: Auxiliary					x									
	Other	Brushing + Linking		x	x		x									x
	Transitions	Time		x	x	x		x	x	x			x		x	x
		Space	x	x				x				x			x	x
		Filter / Selection		x			x					x				
		Views					x									

Table 7.1: Classification of data, visualizations, and interactions of the case studies.

In the table as well as the Appendix, we refer to our case studies as **VU** - Venice Unfolding (Chapter 2), **M** - Muse (Chapter 3), and **TT** - Touching Transport (Chapter 4)[1]. For the visualization and interaction techniques we occasionally refer to the specific prototypes, with Venice Unfolding and Touching Transport each having one, and Muse having three (M0, M1, M2).

This helps us identifying recurring challenges in interactive geovisualization for casual use, and grounding the discussion of our contributions in regard to the case studies. We refer to their respective chapters for our design considerations and other details.

7.2.3 Discussion

Based on the classification and the contribution of the case studies we identify and discuss some general lessons learnt when constructing geovisualization for casual use.

Attract users in semi-public settings

We have described how we designed our systems in ways casual users found it fun to use, and interacted with the information visualizations on large tabletops installed in semi-public spaces. In Venice Unfolding, we provided novel interactivity with a compelling looking tangible object. This polyhedron enables playful exploration of multi-facetted data. In Muse, we managed to attract conference attendees to explore the data by providing personal relevant data in established visualizations. In casual settings, users first have to be attracted to the system in order for them to start exploring the data. Each prototype provided at least one large map visualization, which people were most accustomed with both understanding the displayed data as well as the interaction possibilities. In the map views, we reduced visual complexity by balancing level of details in the base maps between a simple visual style (to not overwhelm users with complexity, and to not interfere with visualized data atop), and sufficient geographical features (to allow viewers to understand geo context and to orient themselves).

[1] Besides the three main case studies included as chapters in this thesis, I designed a number of further geovisualizations for casual exploration to investigate how to support users to gain insights into different domains. “Foreign Domestics” (FD) won a large visualization competition, “A day in Berlin” (VBB) was used to demonstrate visualization at the official release event for Berlin’s open transport data, and two were exhibited internationally at design exhibitions: Shanghai Metro Flow (SMF) in Shanghai, and Bumping Borders(BB) in the United Kingdom. See appendix for all visualization projects (A.3) related to this thesis’ topics.

Visualization systems in semi-public spaces should invite users through curiosity and aesthetics so they will be attracted to the system, start playing with it, and finally explore the visualized data. The systems should be designed in ways to engage such audiences to keep exploring the system, and to facilitate serendipitous discovery. Through our case studies, we have learnt that this can be achieved by showing visually pleasing yet simple visualizations on large interactive tabletops.

Intuitive multitouch interactions

Basic tapping interactions works best for a audience of casual users. Users tried to tap the menu element in Venice Unfolding, while our prototype only offered moving the polyhedron towards the element for selecting it. In the first Muse prototype, people tried to tap an item from the Exploding Menu, while one had to tap, slide, and release to select an item (We solved this in the second prototype). In Touching Transport, users tapped on a row in the time series view, directly, instead of using the time range slider to select that specific time range. While each implemented interaction pattern had a reason, we suggest to at least provide multiple ways of achieving the same task.

Overall, we also learnt that one should provide simple multitouch interactions. Our design decision to focus on self-explanatory interaction patterns and avoid complex gestures helped users to explore the data set. People encountered few problems with the touch interactions and were able to pan the map and tap to select stops. We are confident that – due to the wide-spread dissemination of smartphones and tablet computers – basic touch gestures are well-known, and can be deployed for audiences in semi-public spaces.

Aesthetics

Chen included aesthetics as one of the top ten unsolved problems in information visualization, and states that it is important to investigate how aesthetics affects insights, and how these two goals "could sustain insightful and visually appealing information visualization" [34].

In our case studies, visual and interface design were guided by principles of information aesthetics [114], aiming to combine accurate data representation with easy-to-use interactivity. Besides the visual form, aesthetics concern aspects such as originality, innovation, and further subjective factors comprising the user experience [188]. In order to design visualization systems easily understood and enjoyed by the users, we used an attractive and minimalistic visual style.

Another aspect in visualization aesthetics is its fluidity, including the use of animated transitions, the immediate response of the system, the use of direct interactions, and continuous exploration possibilities [51].

We merged theses two aspects and designed systems with reduced visualization complexity. In Venice Unfolding we integrated facetted browsing with a map display in a single unified view. In the iterative process of designing Muse, we went from coordinated multiple views (M0) to single views (M1 and M2) due to user's feedback. Touching Transport has three distinct views, but shows one visualization at a time, rather than all three simultaneously, in order to lower visual complexity for casual users. In a recent visualization study, Van den Elzen and Van Wijk "focus on non-expert users, who want to explore data incidentally, who are not used to complex multiview displays, and require as simple as possible means to explore their data" [186]. Providing different less complex perspectives into the data is a crucial step in this.

As discussed in Section 7.2.4, it is important to value user's satisfaction in visualizations for casual use. Participants in our Venice Unfolding study found the visualization system appealing, conference users in our demonstrations of Muse liked the system and found it aesthetically pleasing. With Muse and Touching Transport, we have demonstrated that visitors in semi-public spaces were attracted to the visualizations, and shown with Touching Transport that this enables lay people as well as experts to explore the data. Hence, with our case studies we have demonstrated that aesthetics and functionality work together, and support casual users to enjoy the systems.

Design guidelines are an established way of summarizing knowledge, and have great merits in supporting designers to ground their design decisions. However, they might not fully cover all interwoven aspects and might be inadequate for the holistic qualities of aesthetics. Hence, we stress the additional need of internalizing knowledge through design practice. Ideally this results in craftsmanship, which can be "characterized as the skillful and coherent integration of all relevant design dimensions" [134]. We will discuss the craft of designing visualization systems in Section 7.5.3.

Summary

People used the prototypes from our case studies in user studies, on conferences, and in exhibitions to learn about the domain, have a good user experience, and discuss their insights with others. We have shown how different stakeholders can be empowered to understand tempo-spatial data by designing and combining interaction and visualization techniques, while still attracting casual users with simple and compelling visual style.

7.2.4 Contributions and Conclusion

Design of Case Studies. We have created and evaluated interactive visualizations of tempospatial data for casual use in three case studies. We have selected visualization methods to map the data in question to appropriate visual representations for the respective data sets. We have developed all three geovisualization systems for large interactive tabletops, and selected interaction techniques to support exploration of the data. We have shown that a careful adaptation for casual use can help non-experts finding it appealing and are inclined to start exploring the visualized data. The aesthetic composition of established techniques lead to people understanding the data. And most importantly, we have shown that in these ways people with different backgrounds can be supported to gather insight.

Evaluation of case studies. In the iterative user centered design process of our case studies, we employed a variety of evaluation methods (see A.1.6 for details on the evaluation methods used). We incorporated testing throughout designing our prototypes, as different tests are appropriate at different stages of the development process [180]. In their paper on casual information visualization, Pousman et al. discuss how evaluations of information visualization systems increasingly shift focus to user satisfaction instead of solely measuring usability and efficiency [156]. In order to validate the effectiveness of our visualizations in regard to support gaining insights in casual use, we demonstrated rapid prototypes quickly and often to users. As one of the main objectives was to verify these systems to work in casual setting, we demonstrated our complex functional prototypes in real-world settings, and employed in-the-wild evaluations. We described and justified our approaches. We are going to discuss the implications of the lessons learnt in our multi-project design process in Section 7.5.

Classification of case studies. In multiple case studies we have constructed functional prototypes with actual data. The concrete design decisions and implementations result from the specific aims, design considerations, and visual experiments in the design process. We described some of the recurring design challenges and our chosen techniques with the help of a simply classification in Section 7.2.2. Our contribution lies in the organization of the employed techniques into groups, and the classification according to a simple taxonomy, in order to gather common themes, and to verify general applicability. We will reflect on this approach in Section 7.5.1.

7.3 Visualizing relationships (RQ2)

In this section, we describe and discuss our investigation on visualizing relations between geo-referenced objects, and summarize our contribution in 7.3.3.

In each case study, we investigated how such multivariate relations can be visualized for casual use. We pragmatically selected and designed relationship visualizations appropriate for the specific design goals and data sets. Yet, the lessons learnt in one case study affected our design considerations in later ones. After problems occurred with users having troubles correctly interpreting the connections of the first multitouch prototype M1 in case study 2, we conducted a controlled user study on weighted connections (see Appendix A.2) to inform the design of prototype M2. While designing the visualization system in TT, we encountered a new need of visualizing not only weighted edges, but revealing multiple weighted edges in a linear node graph. Thus, we explored ways of extending arc diagrams to solve this problem, and developed the Sankey Arc technique.

7.3.1 Summary

Visualizing relationships on maps

The general question of RQ2 was how to visualize multivariate relationships between geo-referenced data. This can be further specified for each case study:

- *Venice Unfolding:* How to visualize multiple relations between urban redevelopment projects based on classification similarities from an architectural taxonomy?
- *Muse:* How to visualize relations between scientific institutions with varying strength based on co-authorship?
- *Touching Transport:* How to visualize ridership relations between sequential public transit stops?

In the following, we will describe selected characteristics of relations based on our classification in Section A.1.3, and describe the chosen visualization approaches.

Venice Unfolding. The displayed network shows conceptual relations between urban redevelopment projects. While the network dimension of the architectural projects data set is many-to-many, the visualized network is one-to-many, as only one project is selected at a time. For additional edge attributes it uses single-after-filter. The relations between projects are non-weighted.

Figure 7.1: After selecting a term from the taxonomy via the polyhedron interaction, relations between the currently selected project and projects with the selected term are displayed in Venice Unfolding.

The Venice Unfolding prototype enables faceted filtering, and shows connections between matching projects after a user selected a value from a category (Figure 7.1). Lines represent relations based on same attributes of currently selected category. While the lines are thin and visually low-key, they double encode a relation together with the highlight of the related project markers.

Muse. This case study uses lines representing relations between research institutions based on co-authorship of publications. In both prototypes, the strength of inter-institutional collaboration was based on the number of publications.

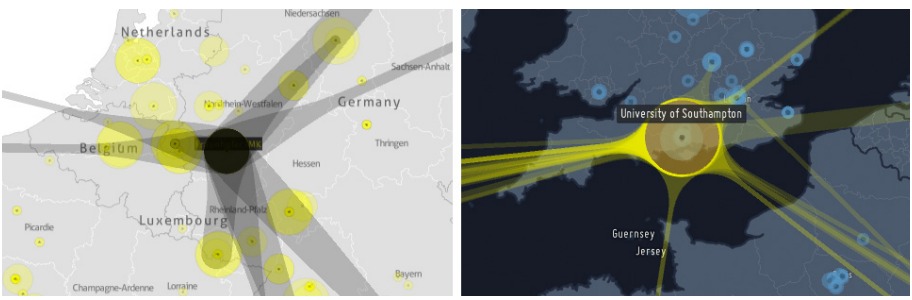


Figure 7.2: (a) Muse-1 using GumConnections, and (b) Muse-2 using weighted connections to show relations between institutions.

In the first prototype, we tried to mitigate occlusion problems typical in network displays on maps by using GumConnections to show spatial glyph connectivity. This helped users to understand which marker a line was connected to, even if multiple lines are in vicinity. However, GumConnections do not show weight, but use varying thickness as a graphical metaphor to signify distance (Figure 7.2a). In the second prototype, we visualized relation strength through the thickness of the edges. To adhere to the Gestalt law of good continuity, with this technique we still use smooth connections at the end points of the edges (Figure 7.2b).

Touching Transport. In Touching Transport, one of the three visualization modes, the arc view, visualizes rides of a bus line as connected arcs between stops. The network dimension of the bus stops is one-to-one, as the stops of a single bus line are (typically) sequentially. However, the network dimension of the passenger data is many-to-many, as passengers can go from any stop to any other. The edges have a weight, signifying the accumulated number of passengers traveling from one station to another.

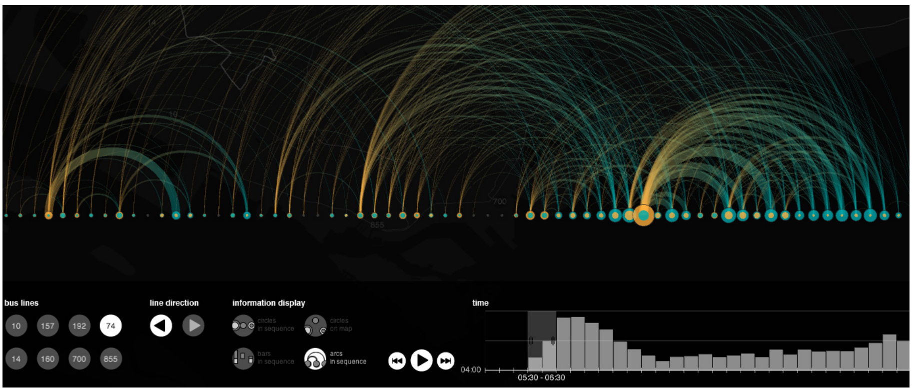


Figure 7.3: Arcs showing rides of a bus line for the selected time range on a tabletop (cutout).

It uses arcs to show connections between stops laid out in one dimension. These arcs have varying thickness and are color-coded to visualize number and direction of passengers of a route. The problem, as demonstrated in Section 5.6, lies in the overlappings of the arcs at the node base (Compare prototype with weighted arc diagrams in Figure 7.3 to the one with Sankey arcs in Figure 5.7).

Visualizing weighted relationships in path graphs

This culminated in the general question we tried to find a solution for.

- *Sankey Arcs:* How to visualize edge weights in path graphs?

Previous arc diagram solutions suffer from displaying all arcs at the center of a node, which can lead to visual obstruction. The aim of our Sankey Arc technique is to improve clarity, to enable users perceiving and comparing weighted edges in path graphs.

7.3.2 Discussion

Arc diagrams are an established method to visualize relations between nodes in a simple path graph. In order to understand the design space of arc visualizations, we conducted a formative survey [141]. We collected various examples with different characteristics both from scientific publications, as well as from the design community in order to get a wider sample of arc diagrams. Based on that collection, we identified and grouped properties of arc diagrams (such as node distance, node seriation, arc directionality, etc.), and classified the collected diagrams. This helped us to generalize the applicability of our Sankey Arc technique.

7.3.3 Contribution and Conclusion

Triggered by the recurring requirement of revealing relations between geo-referenced places, and motivated by the challenge of visualizing additional properties of such relations in a visually low complex and aesthetically pleasing way, we employed different edge visualization techniques in our case studies. Based on the various design requirements and the lessons learnt from designing and evaluating our prototypes (not least due to our controlled user study on weighted connections), with Sankey Arcs we developed a novel technique of showing weighted connections in a path graph. We described the algorithm, and discussed its advantages and limitations. We have demonstrated that this improved arc diagram technique helps viewers comparing nodes and their edge weights.

On the side, we highlighted the visualization of relations as a prime example of how the design of different case studies and the identification a recurring problem in geovisualizations helped us inform the development of a new visualization technique.

7.4 Supporting geovisualization construction (RQ3)

This section discusses RQ3, and summarizes our contribution in Section 7.4.3.

The development of this library was guided by the goals and outcomes of geovisualizations for casual exploration for non-experts. We have identified the three task groups of learning, prototyping, and creating. We explained our reasoning behind grouping tasks in this way, and described the respective users and their goals in detail in Chapter 6. We have explained the design decisions of the library, and compared it to related approaches. We have developed the software architecture of a library in such ways to provide appropriate means to support a wide variety of projects[2]. In the following we summarize our contributions for each task group, and bring references up to date since the publication of the paper.

7.4.1 Summary

Supporting learners was motivated by our own teaching as well as a call for action by leading geovisualization researchers [124]. The library facilitates students and other beginners to explore the opportunities of geovisualization, and assist them in gaining skills to progress to one of the other groups. In the last years, Unfolding has been used in international university courses from interaction design, to computer science, to architecture and urban studies. In Chapter 6, we have shown that users of this group were satisfied with the simplicity and learnability of this library, and demonstrated its use with successful student projects.

We have used it in our own projects to develop and evaluate novel techniques, e.g. the *Exploding Menu* to reduce the fat finger problem in selecting overlapping glyphs common in geovisualization (see Chapter 3). In addition, it has been used to develop novel methods in geovisualizations in a diverse set of projects. Liquidata introduced an interaction method bridging personal and public space, where users place their smart phone onto a tabletop in order to share visited places [57]. In the same project, Unfolding also helped creating an animated fluid shape signifying these places in order to convey the imprecise mental map to the viewer. Another project has put Unfolding in use on one of the highest resolution tiled displays in the world [183] in order to explore how people interact with maps on very large wall displays. Another highly explorative project applied Unfolding on a physical platform for interactive data visualization on three-

[2] In order to support developing visualization systems for interactive tabletop and surfaces, we created a simple multitouch library. See A.4 for an overview on our additional software libraries and components.

dimensional surfaces [49], where people can hover their finger and highlight data entries for the selected area the finger points to. We have shown people for both sub tasks in the prototyping group were satisfied with the applicability and suitability of this library, and demonstrated its use with successful projects.

7.4.2 Discussion

In his EuroVis 2014 keynote talk, John Stasko identified making the constructions of visualizations easier as one of the key open problems in visualization [175]. His statement reaffirms this line of thought within the visualization community. Since the beginning mainstream adoption of information visualization in recent years, it has been argued that visualization researchers have to provide tools to support lay users creating visualizations so they can visually explore their datasets [77], as well as for designers who need to communicate data but are not necessarily visualization experts [21].

Trying to fulfill the conflicting requirements of flexibility and ease-of-use, researchers have developed tools ranging from visual applications with a user interfaces, to software libraries for developers. In their recent survey on visualization construction, Grammel et al. identify six distinct approaches, with *textual programming* as the one giving fullest freedom to create custom interactive visualizations and the analysis of data in non-standard ways [65]. While this requires technical savvy users having programming skills it allows fully custom visualizations[3]. In their study on how designers work with data, Bigelow et al. argue that visual tools with a fixed set of features limit the design space, and thus reduce their applicability for designers [21].

Grammel et al. underline the increasing need to design visualizations as the demand for “rapid visual data exploration” as well as for “engaging communication through custom visualizations” grows [65]. Both closely match definitions of task groups we identified in our Unfolding paper, and are supported by the library; the former fits our task group of prototyping, and the latter our group of creating. Beyond savvy and expert users, with Unfolding we also managed to support novice users.

7.4.3 Contributions and Conclusion

A further main contribution of this thesis is the Unfolding library to create interactive maps and geovisualizations. Both constructing the prototypes in our case studies, as well as collecting feedback from visualization projects by

[3]See the related work section (6.3) in chapter 6 for an overview of other approaches.

others has helped us to adapt the library, and to repeatedly refine its function range. We have shown that our software library supports a diverse set of users, and eases developing visualizations of geo-referenced data. The results from our user survey indicate that Unfolding achieved our design goals. We see the use in various courses, in student, research and commercial projects as further indicator for the learnability and usability of the library.

Unfolding is well established, and the most used library for maps and geovisualizations in the Processing community. Since its first public launch in 2011 it has been downloaded over 15,600 times[4]. Presentations about Unfolding have been viewed more than 38,000 times on SlideShare[5]. Unfolding has been used successfully to create geovisualizations for non-experts. Besides the three case studies within this thesis, it has been used among others for applications on interactive surfaces (e.g. [183, 57, 147, 49]), and for communicating large sets of time-varying geo-referenced data to a lay audience (e.g. [177, 138, 43]).

In this section, we have summarized our contributions with this library, and proven that Unfolding is used successfully for its intended use cases. We have reflected on current trends in visualization research, and shown that our software library is an appropriate way of supporting the construction of geovisualization for non-experts, and beyond.

7.5 Discussion

In this section we discuss and reflect on some of the major lessons learnt while designing the case studies, and pursuing the research within this dissertation.

7.5.1 Multiple case studies as annotated portfolio

As others have argued, a collection of useful design examples is a core aspect of design research [60], and can help moving forward the craft quality of a design discipline [10]. Gaver defines a portfolio as follows: "If a single design occupies a point in design space, a collection of designs by the same or associated designers – a portfolio – establishes an area in that space." [60].

By consolidating our three case studies in this thesis we provided a collection of geo-spatial data visualization for non-experts as portfolio. With each case study, we investigated its specific domain while addressing the shared main

[4] Downloaded versions: 3000 × v0.8 (Aug 11–Aug 12), 6000 × v0.9 (Sep 12–Jul 13), 6100 × v0.9.3 (Aug 13–June 14), and 500 × v0.9.5 (July 14). Rounded to next hundred.

[5] See http://www.slideshare.net/tillnagel/presentations?order=popular

goal of enabling a casual exploration of geo-referenced data on a large tabletop system demonstrated in semi-public space. All had in common that the shown data was relevant for non-experts in a casual use scenario. However, as we have summarized in Section 7.2.1, each data set was different in its specifics, and exemplified different aspects of tempo-spatial data. We also documented similarities and differences in the chosen visualization and interaction techniques in Section 7.2.2. Hence, our collection can serve as viable guide for other designers and researchers investigating visualizations on tabletops in casual settings (cf [85]).

For this thesis, the publications on each case study co-act as annotations for the artifacts. However, only by framing them within the common research questions, and identifying common challenges and solutions, we highlight features of interest in our work [24]. We see the concept of annotated portfolios to be beneficial to our field at the intersection between visual design and computer science.

7.5.2 Designing and evaluating visualization systems for casual use

Within each case study, we developed one or more functional prototypes in an iterative design process. The question arose how to evaluate a visualization for a audience of lay people. As the use case always was to enable casual exploration, we demonstrated the systems to different stakeholders. We used a mixed-method evaluation approach, which included evaluating each systems with users. We demonstrated the value of our designs by exhibiting the prototypes of the latter two case studies, and gathering feedback from real users in in-the-wild studies.

For user studies to be useful the tool has to be polished [180], i.e. the functional prototype should have all desired functionality, and fulfill all design requirements needed for the user. Otherwise, as Tory et al. state, missing features can influence the results of user studies [180]. And while they propose as a solution to “focus on design ideas rather than complete visualization tools” they also acknowledge the challenge that taking parts out of context may render the tool useless. In contrast, Sedlmair et al. argue that quickly developing prototypes is crucial in design studies, and call non-rapid prototyping a pitfall when designing visualizations [166].

In our case studies, we learnt to combine the best of both worlds. Firstly, we developed small-scale visual experiments in the process, both for understanding the data ourselves, as for getting feedback from experts. Domain experts often do not have the necessary knowledge nor vocabulary to express what their want in terms of geovisualization. Designing data experiments has been useful to communicate to experts the benefits of data visualization, and to prime them to come up with interesting ideas and empower them to formulate their visualization needs. Secondly, for in-the-wild studies we argue polished prototypes are important. Still, this should not lead to overcommitment to the prototype.

In summary, we encourage designers and researchers to polish visualization systems on ITS for exhibitions. For evaluating novel techniques in a lab study it is not always necessary to refine all parts of the implementation. However, when exhibiting a visualization prototype to gather feedback from people in a semi-public setting as urban demo we recommend to focus attention also on an attractive visual style and an elegant user interface even in areas not currently under research. To reach such polishness in the design of the tools, craft is important. However, when creating visualizations it is important to balance the prototypes' polishness with the rapidness of the prototyping in the design process.

7.5.3 The importance of craft

Designing an information visualization system is a craft activity, in which the designer uses his knowledge of concepts and techniques and combines it with novel ideas to create an innovative result [172]. We consider both design and implementation as a craft activity when creating visualizations (see also our discussion in Section 4.7). Spence notes that the success of a new visualization tool "depends upon the designer's understanding of the task for which the tool is intended, as well as the designer's possession of many and varied skills ranging from visual design to algorithm design" [171] (as cited in [41]). However, the expertise of visualization designers is implicit rather than explicit [41]. Similarly, in their book *The Craft of Information Visualization*, Bederson and Shneiderman state that they have "developed an intuition about what makes information visualization [...] interfaces work well" [17]. Designing case studies helps building such intrinsic knowledge through design practice. Studying design practice not only allows learning from meaningful artifacts but from useful descriptions of their composition, and user responses [10]. In the same sense, researchers in the field of information visualization on interactive tabletops have underlined the need for more reports and evaluations around the deployments of such work [98].

With this dissertation, we contributed to the craft of designing geovisualizations for casual use twofold: through our design artifacts, and through our geovisualization library. With the former, we not only gained further implicit understanding in order to better create effective and well working visualizations for new audiences, but support others to learn from them through our discussions of their design and use. With the latter, we assist people to acquire experience by easing the creation of visualizations in order to gain design skills.

7.6 Future Work

As geovisualizations on interactive tabletops for casual use is still a rather recent and evolving area, there are numerous open challenges and future research objectives. Isenberg et al.'s agenda for research at the intersection of interactive surfaces and data visualization identify three areas, and define technical, visual design, and social challenges [98]. In their follow-up work, Isenberg and Isenberg collect and classify relevant literature, and create a systematic overview of open challenges [97]. As they stress the need to adapt and redesign visualizations to be perceivable and interactively modifiable on interactive surfaces, in the following we suggest research on one visualization technique and on one interaction technique stemming from our lessons learnt as practical challenges. We then proceed to briefly discuss future directions in the design space of geovisualization on ITS.

Bivariate symmetric data glyphs on maps. A common visualization task is to show bivariate data for geo-spatial locations, often to visualize symmetric properties (such as import and export of goods). In his taxonomy of bivariate maps, Elmer discusses combinations of two visual variables with two symbol dimensionalities, and classifies different visualization techniques for the herein discussed use case of point based symmetric data [50]. In Touching Tranport, we considered three visual encoding methods for displaying boarding and alighting passengers on the map: stacked bar graphs, pie charts, and concentric circles. Comparing charts at different locations correctly is challenging with bar charts on geospatial maps due to the varying baselines, but are feasible with circular glyphs. With pie charts it is difficult to compare values due to perceptual issues in comparing complex shaped areas. To avoid these drawbacks, we chose to use two overlapping circles both being scaled according to their value. The circle encoding the larger value is displayed as outer element, which guarantees that both always are visible. Furthermore, it aims to help viewers quickly identify boarding and alighting characteristics of different bus stops. However, we did not verify if our assumptions of the selected technique are correct and how it compares to other methods. Thus, there is the need of a controlled user study with non-experts evaluating different techniques to find the most effective and efficient method for visualizing bivariate symmetrical data for point locations.

Multi-touch time range slider. Selecting, aggregating and filtering time is an important task when exploring tempo-spatial data. While there is a wide range of established techniques to manipulate temporal data, in our case studies we aimed at providing easy-to-use interaction mechanisms for casual use, and incorporated basic time range selection mechanisms. However, while people dragged the time slider with ease in Muse and Touching Transport, fewer fully used the time range mechanism. As range sliders are an established interaction technique [1], and seem to be especially fitting for dual finger input [19] to drag both handles, it needs to be further investigated whether our implementation in Touching Transport can be improved in order to most effectively integrate them on large multi-touch devices.

Design and evaluation guidelines. Design guidelines are an established way of summarizing knowledge, and have great merits in supporting designers to ground their design decisions. In the field of visualization on tabletops, there still is lots of ground work to cover, and researchers call for "clear surface-specific guidelines" which "will help us develop visualization applications and, consequently, increase the audience that benefits from visualization use." [98]. In this dissertation, we summarized the contributions of our case studies in the field of geovisualization on tabletops for casual use, and discussed design guidelines both for visualization design, as well as for the design process. The open challenge is to expand on this, collect lessons learnt and best practices from a wider set of case studies, and generalize such design guidelines. A primary goal is the creation of a "catalogue of design considerations for a variety of visualization, interaction, and surface types" [97] by generalizing common challenges, pitfalls, and design solutions. However, this should be accompanied with an annotated portfolio in order to maintain some of the complexity, richness and interrelation of the design decisions [85]. Together, this can result in a holistic description of the design space of geovisualizations on interactive surfaces for casual use.

7.7 Closing Remarks

A significant contribution of this thesis is the portfolio of case studies. With each, we investigated concrete challenges in their domains, and designed successful and working visualization systems. With our case studies, we provided innovative solutions to research question RQ1 by bringing together computer science with design in order to create geovisualizations on interactive tabletop and surfaces for casual users. The design and description of our case studies, the explanation of our methodologies, and the discussion of our findings are important parts of our contribution. Moreover, the developed prototypes themselves also act as artifacts which encapsulate our design decisions, and thus embody parts of our research results.

With our novel Sankey Arc technique, we made a small albeit sound contribution to the specific problem of improving the visualization of weighted relations between nodes in a path graph. Moreover, it acted as a representative example for identifying a recurring problem in case studies with similar characteristics, and designing a solution for it.

With our Unfolding Map library, we made a major contribution to the set of tools which support the construction of geovisualizations. Firstly, the library is an effective means to create state-of-the-art geovisualizations. Secondly, we contributed to the field by discussing new audience groups of developers, and reporting on their use of our library. And lastly, by easing the development of geovisualizations, the library empowers people to investigate the aforementioned research areas.

In the intersecting research fields lie visualization and interaction challenges, and new ways of developing and evaluating such systems. With the work discussed in this thesis we hope to motivate and further enable a new design space for casual exploration of geovisualizations.

Appendix A

Appendix

This appendix contains the classification of the case studies (A.1), the preliminary study on weighted connections (A.2), and a enumeration of my other visualization projects (A.3), as well as one on my other libraries (A.4).

A.1 Classification of case studies

In this appendix, we will give a summary of the objectives and domains of the three case studies, a systematic overview on their visualization and interaction methods, and identify recurring challenges in interactive geovisualization for casual use. This grounds the discussion of our contributions in regard to the case studies.

A.1.1 Aims and Domains

The domain objectives for each case study were based on general task analysis and interviews with domain experts. At highest level, they can be described as to support citizens participating in redevelopment process (VU), scientists socializing with colleagues, and initiating new collaborations (M), and citizens and experts reaching a common understanding of urban mobility (TT). The more concrete aims for the interactive visualizations were to support interested stakeholders to

- Learn about redevelopment projects, their properties, and their relations (VU)
- Learn about collaboration between and similar research interest of institutions (M)
- Learn about spatial and temporal patterns in public transport (TT).

In all case studies, the visualizations were targeted at lay users who might, however, have a certain level of prior knowledge or interest in the domain.

As a side goal, two of the three case studies were intended to provide a backdrop for different stakeholders. While the main target audience still were the lay people, with Venice Unfolding we sought to bring together citizens and urban developers, and with Touching Transport to bring together citizens and transport planners. In this way, non-experts learn about the domain through the visualized data, and experts about what the non-experts might learn.

A.1.2 Data

The data for the case studies came from various sources, from architectural taxonomies and repositories, to custom harvest scripts, to databases and text files from our partners. After acquiring and parsing, the data had to be filtered and mined before it could be represented to the viewer (cf. visualization process in [59]).

Data has three main characteristics; the inherent meaning of the data are its semantics, the contained patterns, relations, and trends are the behavior of the data, and the organization of the data are its structure [21]. Time and space have inherent semantic structures, whereby they differ from other common data dimension. While the separation between scientific and information visualization is not clear cut, the main distinction is that infovis has to invent representations for abstract data. In this sense, geovisualization merges approaches from both fields. For each of our case studies, we had to consider appropriate visual mappings depending on the specific characteristics of the data.

Temporal data consists of elementary primitives (points or intervals) and their relations (structure). Their temporal occurence (frequency) and granularity (precision) can be classified [4]. Different types of events happen with different frequency, and in different spans. Some of the frequencies are regular such as seasons or weekends, others are less regular such as social cycles (like holidays), or natural cycles (such as tides or volcanic activites). In our case studies, we investigated human created irregular (urban redevelopment in VU) as well as regular frequencies (conference dates in M, and time schedules of public transit in TT). The precision of the temporal data relies on the available data, the aimed for performance of the system, and the characteristics of the chosen visualization technique.

A.1.3 Geovisualizations

Maps.

In all but M0 we used a base map showing selected geographic details. Geographic base information in all cases came from OpenStreetMap. In all case studies we adapted the map style to fit the visual style of the visualization, and to not obstruct the overlaid information.

Figure A.1: Background maps of the case study prototypes.

Geographic positions. All three case studies show markers at their geographic position, instead of using other geovisualization techniques such as isolines or choropleth maps. This is due to its simplicity which eases understanding the visualization. The visualization techniques differ, however, in how they encode additional data; from showing only dots (VU), to graduated symbols (M), to bivariate glyphs using overlapping concentric circles (TT).

Metadata. Metadata can be shown mostly in two ways: As tooltip over a specific object in which additional related information is displayed. They can contain text (VU, TT Map, TT Time Series), media files (VU), or even further graphs (TT Map, TT Time Series). The other typical way of displaying metadata is by having a dedicated area (M0). Both methods are a detail-on-demand design pattern, and appear after the user selected the main object (e.g. by tapping on a marker in TT Map), or chose from a menu (e.g. by rotating VU's polyhedron).

Relation visualizations

Here, we describe the different techniques in visualizing relations between geo-positioned marker. This section is more detailed as it is used as basis for our discussion of displaying relations Section 7.3.

Generally, a graph represents a network consisting of a set of objects (called nodes) where some of them are connected to each other by links (called edges). The following categories and their values are based on the classification of [117] and [16].

Network dimension. The dimension of a network describes the linearity. Nodes can have no, one-to-one, one-to-many, or many-to-many relations between each other. The first trival category of none is excluded, as we are focusing on the visual display of connections.

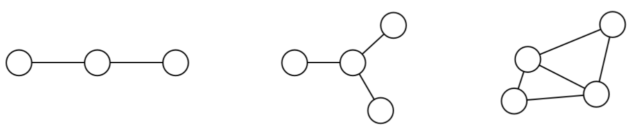


Figure A.2: Nodes having a) one-to-one, b) one-to-many, and c) many-to-many connections.

While we are showing a many-to-many graph to represent the public transport network of Singapore in the background of the map view in Touching Transport, all three views highlight a single bus line at a time, and thus visualize one-to-one, i.e. linear path graphs. The most common network dimension is a many-to-many, which is used in Muse prototypes 1 and 2, and Venice Unfolding.

Edge weight. Links between nodes can have additional properties. When these properties have a numeric value they can be seen as edge weight. A graph can be weighted or non-weighted.

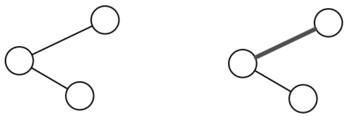


Figure A.3: Nodes having a) non-weighted, and b) weighted connections.

In our case studies, M0 and M1 contains non-weighted graphs which shows an edge between research institutions independent on their potentially different strength. In M2 we incorporated some calculated weight based on the amount of co-authored publications. In TT, we used both weighted and non-weighted graphs: The map view displayed simple lines to show the sequence of a bus line, while the arc view visualized passenger rides between stops.

Edge attributes. Besides weight, edge can have additional properties describing not one of the connected nodes but the connection itself.

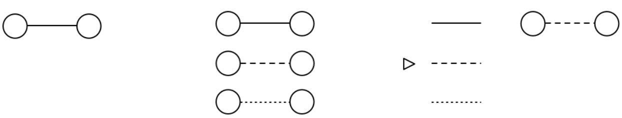


Figure A.4: Edges having a) single, or b) multiple categories, and c) single-after-filtering.

All Muse prototypes have single attribute connections, while Venice Unfolding and Touching Transport both have multiple categories. After people use the polyhedron filter mechanism, connections of that selected category are shown. In TT, people can select bus lines and bus line directions via the auxiliary control panel, which then is shown in all three views.

A.1.4 Interactions

Map Interactions. People could use common map interaction patterns in all case studies, from slide-to-pan, to pinch-to-zoom, to tapping on geographic objects to automatically zoom and pan so the selected object fits in the view.

The first two simple methods have been implemented in all three case studies (VU, M1, M2, TT Map), the tap-to-fit only in M0 and TT Map.

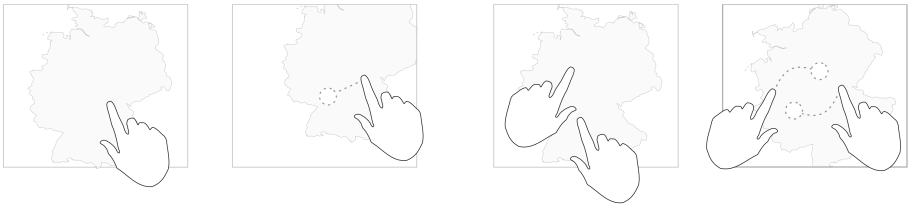


Figure A.5: Map interactions: a) slide to pan, and b) rotate to re-orient map.

Select Item. Selecting an item for further inspection is a common interaction, with the task reaching from getting details-on-demand (VU, M, TT), to updating another view for linked objects (TT). In all our case studies, users could select a marker by tapping on it with their finger.

However, occlusion is a common problem in visualizing spatial data on interactive maps if there are too many data points in close proximity. It is an even higher problem for touch interfaces due to the fat finger problem [160]. The simplest solution is to provide an interactive map in which users can zoom in to enlarge the area of interest, thereby increasing the distance between geo-positioned glyphs, and thus resolving the overlapping problem. While being simple it might become tedious, and works only for symbols not on the exact same position. Techniques developed to solve this problem are snap-to-target, loupe or lens metaphors, or dual finger input [19]. In M1 we developed Exploding Menu, an adaptation of the target expansion technique [14] for geographic markers.

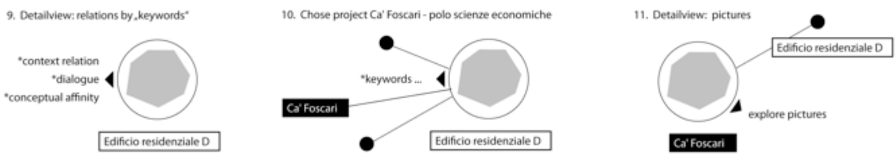


Figure A.6: Filtering in Venice Unfolding (detail).

Other. We designed novel or extended methods of visualization and interaction techniques. These ranged from a stacked donut graph to show distributons change over time (M0), to a multitouch time range slider (TT, to adaptable small multiples to let users filter frequency and precision for comparions (TT).

A.1.5 Multitouch Hardware

Each case study was designed for a large tabletop with high resolution screen and multitouch interaction capablities. However, the technical and functional specifications of the devices differed. We describe the tabletops according to classification categories from a survey on visualization on interactive surfaces [97] (in which all of our case studies are included).

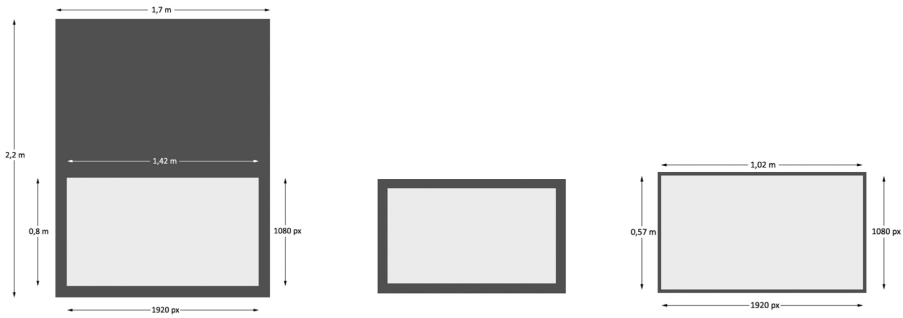


Figure A.7: Interactive tables used for Venice Unfolding (left), Muse (middle), Touching Transport (right, middle).

Venice Unfolding investigated a new tangible interaction mechanism to ease facetted filtering, thus this device required capabilities to track different physical objects. We utilized a tabletop we designed and constructed for a previous interactive exhibit (see [142]), allowing us to track different fiducial markers on the sides of Venice Unfolding's polyhedron. The tabletop uses diffused illumination (DI) for tracking, and a projector for display. The screen dimension are 1.42×0.8 square meters with 34 pixels per inch (ppi). For Muse, we constructed a lighter and more robust table in order to easily transport it to different conference venues. The tabletop uses laser light plane (LLP) for tracking, and a projector for display. The physical size of its screen is 0.96×0.54 sqm with 50 ppi. And while we used a commercial tabletop in Singapore, we deployed Touching Transport onto two devices with comparable specifications. The commercial tabletop uses DI for tracking, a TFT LCD for the display, and has a 1.01×0.57 sqm large screen with 48 ppi. The second one is the same as from Muse. This was due to the setup of our study, which was conducted at two distant locations. As a side effect, this also demonstrated the prototype's portability to different environments. In the prototype we only used finger gestures as input mechanisms which were trackable by both hardware systems. We calibrated both devices in order to have evenly matched input (tracking) and output (color display) capabilities.

A.1.6 Evaluations

We used a mixed method approach of quantitative and qualitiative studies.

			Venice Unfolding	Muse			Touching Transport			
				Muse 0	Muse 1	Muse 2	General	Map	Time-Series	Arcs
Evaluations	UWP	Interviews	x		x		x	x	x	x
	VDAR	Laboratory Observation and Interview	x							
	CTV	Field Observation and Interview			x	x				
	UP	Controlled Experiment				x				
		other	x							
	UE	Informal Evaluation	x	x			x	x	x	x
		Field Observation			x	x	x	x	x	x
		Usability Test			x	x	x	x	x	x
		Laboratory Questionnaire			x	x	x	x	x	x

Table A.1: Classification of evaluations of the case studies.

For the classification of our evaluations we used the taxonomy proposed by Lam et al. [113]. In Venice Unfolding we identified the design goals with urban planning experts (UWP: Interviews), tested the tabletop and the novel interaction method in a lab study (VDAR: Laboratory Observation and Interview), but also did a preliminary usability study with an eye-tracker to test how user performed with the polyhedron (UP: n/a). As our process for Muse included multiple prototype, and a highly iterative approach we employed many evaluation methods over the years: Presenting the desktop prototype (M0) at a conference allowed us to do an informal evaluation (UP: IE), which we followed up with discussions with experts responsible for research valorization (UWP: Interviews) to learn more about how to facilitate scientific collaboration. The following two prototypes on tabletops were demonstrated at different conferences, where we observed and interviewed visitors (CTV: Field Observation and Interviews), and evaluated the visualization in the wild (UE: Usability Test and UE: Field Observation) and asked users for their satisfaction (UE: Laboratory Questionnaire). To improve the visualization of relations, we performed a study on weighted connections (UP: Controlled Experiment) which informed our design decisions for prototype M2. Lastly, in the process of developing Touching Transport, we started with UE: Informal Evaluation, and showed experts from the land transport authority various visual experiments in a rapid prototype approach. While exhibiting the tabletop visualization at a semi-public setting, we observed how visitors approached and used the tool (UE: Field Observation). This was followed up with a detailed lab study to investigate in more depth how people can use TT to gather insights on public transport (UE: Usability Test, and UE: Laboratory Questionnaire).

A.2 User Study on Weighted Connections

A.2.1 Introduction

There has been extensive work using graphical mappings of relation strength (e.g. [1], [2], [3]), but few evaluated how well the visualization performed. Furthermore, in network visualization the two-dimensional placement either is used to plot data, or the exact position does not signify any meaning (e.g. [4]). Displays of network graphs use various layout algorithms to re-position the nodes, in order to reduce visual clutter and network complexity. In contrast, we wanted to select and validate a display style for our geographic use-case, i.e. with imbalanced networks including overlaps, multiple connections with same strength, and, most importantly, where the distance between two nodes is based on geographical proximity, and not based on mapping a data value. Holten and van Wijk [5] encourage the use of user studies in visualization as a lot of informal usability studies focus solely on how much participants enjoyed the applied visualization method. They go on arguing that "[v]isualization evaluation should therefore seek to quantifiably determine how well visualizations perform." Thus, we opted to perform a controlled user experiment, comparing different connection styles in a reduced visual test design (i.e. not in the visual design of the prototype).

A.2.2 User study on weighted connections

We conducted a user study on various display styles indicating the strength of a connection in different ways, as this was one of the issues that emerged in the usability walkthrough of our Muse application. We evaluated efficiency and legibility of the styles to be able to select an appropriate one for the next prototype.

Setup

In each test session, different node networks with four different display styles were shown on-screen, from which the participants were asked to select the node with the strongest connection by clicking on it with a computer mouse. Prior to the test, each participant was encouraged to adapt chair settings, laptop distance, and screen angle in a manner to fit to their usual working environment. These test sessions including the introduction took approximately 10 minutes each. A test session contained five trials, with every trial having eleven runs. The first trial displayed a network without any indication of the weight as dummy for participants to get accustomed to the test setup. Each network consisted of ten nodes, with one highlighted and nine connected nodes. The weights of the connection were randomized with a linear distribution, and ranged from 1 to 9. All nodes were randomly placed within a specified area (to not hit the border). The network was presented to the participants. They were asked to select the node with the strongest connection to the highlighted one. The first run of each trial allowed participants to understand the visual style, and was not included in the analysis. The four different display styles to evaluate were thickness (T), brightness (B), number labels (L), and a combination of thickness and number labels (TL). The display style T maps the strength value onto the width of the stroke used for the lines (Fig. 1a). The style B maps it onto the gray value of the lines, ranging from light gray (lowest) to black (highest strength) (Fig. 1b). The style L uses same-sized, same-colored lines, but displays the actual strength value as text label at the midpoint of the edges (Fig. 1c). For higher legibility we showed the label in black font color on a white background circle. Finally, the style TL combined the thickness and the number labels (Fig. 1d). We did not evaluate a combination of brightness and number labels.

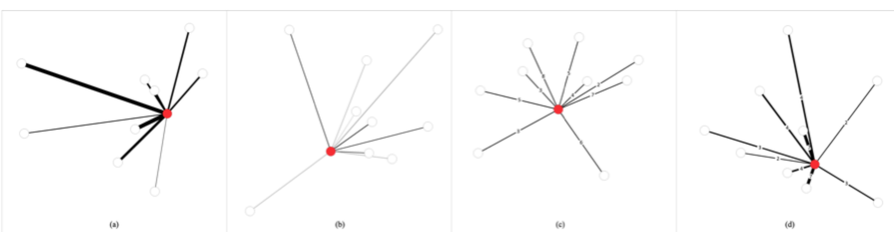


Figure A.8: Display styles with a) thickness, b) brightness, c) number labels, and d) thickness and number labels combined.

Our hypothesis was that the TL style is most efficient, as it helps finding the strongest ones fast and pre-attentively, while still allowing a decision, if strength values are either same or similar. Furthermore, we expected the L and TL style to have the lowest error rates, as the number labels allow exacted comparisons.

Participants

We recruited eighteen participants aged 20 to 25 years from the student body of the KU Leuven (1 female, 17 male). All participants had normal or corrected-to-normal vision. The students all were Computer Science undergraduates, and ranked themselves technically savvy.

Results

The response times and error measurements for each trial were collected during the user experiment. We also stored the generated graphs with the user selected node highlighted. The average response time for style T were 3351ms, for style B 2968ms, for style L 3404ms, and for style TL 3126ms. Summarized, users decided and subsequently selected a node fastest with the style using brightness (B) to map the strength of edges. We measured a binary (correct/wrong) error result, depending on the user's choice. When the participant clicked on a node with an edge strength value of the top two values of the actual strongest ones, we counted it as correct. The average error rate for style T were 14Post-test, we asked the participants, which of the variations they liked most, and why. Out of 18 participants, 7 responded that they liked thickness most (T), 5 preferred the TL combination, 3 the brightness style (B), and 1 the number labels (L), with 2 having no preference. Given explanations by the participants preferring style T were that thickness is easily recognizable, while the numbers (in both L and TL) were difficult to distinguish, as it took time to read and compare them. In post-test discussions, participants argued that TL needed more concentration, and that they felt it demanded a higher mental effort. Still, style TL performed best, even though it was not the style with which participants decided fastest. It was the style users had the lowest error rate, and the second fastest response rate. We chose style TL to be used for the display of the connections between institutions in the next iteration of the Muse prototype. We increased the font size, as six participants were complaining about the legibility, and adapted the font face and the visual design to match the prototype. We based the size of the labels on findings of Ashdown et al [6], and selected a font size of 14pt for display resolution of 50ppi. While the eventual chosen style was not evaluated, we feel comfortable these changes were improvements.

A.2.3 Problems & Future work

Generally, the results of the user study were useful in order to improve legibility and recognizability of the visualization. However, we deem parts of the setup as debatable. A study is needed to test how the performance of a combined style of brightness and labels compares to the others. In the following we briefly describe additional problematic areas, which need further research. First, the study was designed to not provide much time for learning the display styles. Users had the opportunity to interpret each style without time constraints, but there was no further training session. We chose this setup, as real users also will not have that training in a public setting. It needs to be proved if this assumption is correct. Second, we used randomized strength values and node positioning. Synthetic data generation gives control over data characteristics and levels of complexity, "but with the risk of being perceived as unrealistic by analysts." [7] In a follow-up study a more realistic strength set could be used, i.e. according to the actual distribution of publication and institution data. Third, the usage of selecting the node with a mouse, instead of tapping on a multitouch device. We wanted to verify the style independent from evaluating a novel interaction technique. Yet, a future user study could compare these user interface methods. Lastly, three participants misinterpreted the mapping in the first trial. Even though we explained that it had no indication of weight, whatsoever, they selected the nearest node. This influenced their behaviors in latter trials, tending to still select nodes based on proximity, instead of the actual visual mapping. We expect this issue to be solved, when a geographical map is shown in the background. Chen argues, that research in this area "often focuses on graph-theoretical properties and rarely involves the semantics associated with the data" [8]. Furthermore, we did not evaluate how distracting a map with its geographical features (political borders, labels, etc) could be. We plan to conduct this in a less abstract visualization to prove the usefulness in a more geospatial context.

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A.3 Other Visualization Projects

- **Shanghai Metro Flow**. Animated Visualization of public transit network. Plus Poster. In collaboration with Benedikt Groß. Exhibited at the Design Shanghai exhibition 2013. November 2013 – April 2014, Power Station of Art, Shanghai, China, and at the IEEE Vis Art Program, November 2014, Paris, France. http://tillnagel.com/2013/12/shanghai-metro-flow/

- **Foreign Domestics**. Visualization of air travel. Winning entry of the Visualizing.org marathon 2012, the largest student competition with over 1000 participants. KUL, November 2012. http://tillnagel.com/2012/12/foreign-domestics/, http://wms.cs.kuleuven.be/cs/nieuws/nieuwsberichten/till-nagel-viz-marathon2012 (KU Leuven News)

- **A Day in Berlin**. Visualization for my keynote at official release event of Berlin's public transit network as open data. FHP, December 2012. http://tillnagel.com/2013/01/apps-the-city-open-transport/

- **Bumping Borders**. Visualization of cross-border movement patterns based on mobile phone traces. In collaboration with Julian Oliver and Christopher Pietsch. Exhibited at Abandon Normal Devices Festival 2012. http://borderbumping.net/ and http://tillnagel.com/2012/09/border-bumping/

- **United Cities of America**. Visualization for Esquire Magazine. Shows commuting patterns in the USA based on cellphone data. MIT, October 2011. http://senseable.mit.edu/unitedcities/

A.4 Software Libraries

- **SimpleTouch** – Supports basic multi-touch gestures for interacting with visual items. Library provides input interpretation, object manipulation, and an event system. http://tillnagel.com/simpletouch/
- **TimeRangeSlider** – Customizable interactive range slider with animation capabilities. https://github.com/tillnagel/timerangeslider and http://tillnagel.com/2012/06/animated-time-range-slider/
- **GumConnections** – Software components for aesthetically visualizing weighted connections in Processing. http://tillnagel.com/2012/11/gum-and-weighted-connections/

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Curriculum Vitae

Personal Information

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Education

04/2010–01/2015	PhD in Computer Science Doctor in Engineering, KU Leuven, Belgium
04/1997–03/2002	Diploma in Media and Computer Science Diplom-Medieninformatiker (FH), University of Applied Sciences Wedel, Germany

Academic Work Experience

05/2009–02/2014	Lecturer, University of Applied Sciences Potsdam, Germany *Courses on geovisualization and interaction design.*
10/2008–10/2012	Visiting Lecturer, IUAV University of Venice, Italy *Workshops on creative coding and data visualization.*
12/2011–03/2012	Visiting Scientist, MIT Senseable City Lab / SMART, Singapore *Data analysis and visualization, Live Singapore.*
09/2011–11/2011	Visiting Scientist, MIT Senseable City Lab, Cambridge, USA *Data analysis and visualization.*
10/2006–07/2009	Lecturer, Berlin Technical University of Arts, Germany *Courses on creative coding and generative graphics.*

03/2007–04/2009	Researcher, University of Applied Sciences Potsdam, Germany *EU funded project Metadata for Architectural Content in Europe.*

Professional Work Experience

08/2007–08/2008	Freelance Consultant, Werk5 GmbH, Berlin, Germany *Interaction concept and technical consultant for multitouch tables.*
12/2005–02/2007	Software Engineer, Blau Mobilfunk GmbH, Hamburg, Germany *Software engineering, user interface.*
10/2000–05/2004	Head of Application Development, Neteye GmbH, Hamburg, Germany *Team lead, technical consulting, software engineering.*

Invited Talks (Selection)

11/2014	Shifting Perspectives. ShapeShifters Lecture Series, Brussels, Belgium
11/2014	Unfolding the City. Rethinking How People Move in Cities. Architecture.IO conference, London, UK
12/2013	Aesthetics City. Invited panelist at the Design Shanghai exhibition, Shanghai, China
10/2013	Engaging geovisualizations. Microsoft Research, UK
06/2013	Engaging geovisualizations. giCentre, City University, London, UK
07/2012	Mapping the Urban Now. City of Flows conference, Potsdam, Germany
04/2012	Live Singapore. Geoinnovation symposium, ZKM Zentrum für Kunst und Medientechnologie, Germany

Invited Workshops and Guest Lectures (Selection)

12/2014	Guest workshop, Hamburg Media School, Germany
06/2014	Guest workshop, TU Berlin, Germany
01/2014	Guest workshop, Royal College of Arts, London, UK
06/2013	Guest lecture, Dessau Institute of Architecture, Germany
04/2013	Guest lectures, KU Leuven, Belgium
07/2011	Guest lecture, Scuola di dottorato, IUAV Venice, Italy

Awards

07/2013	Best Presentation Award for Unfolding, SouthCHI
12/2012	Winner Infographic for Foreign Domestics, Visualizing Global Marathon

Academic Service

Reviewer IEEE VIS, 2013, 2014

Reviewer CHI, 2013, 2014

Session chair, AVI, 2014

Grant reviewer, Singapore-MIT Alliance for Research and Technology (SMART), Singapore, 2014

Grant reviewer, Freie Universität Bozen, 2014

Program committee, ABIS workshop at the Mensch & Computer conference, 2012

Organizing committee, ADVTEL workshop at the EC-TEL conference, 2011

Session chair, SmartGraphics, 2011

Affiliations and Memberships

Research Affiliate, Data Visualization Lab, KU Leuven

Research Affiliate, Interaction Design Lab, FH Potsdam

Research Affiliate, Senseable City Lab, MIT

Member, ACM SIGCHI, special interest group for computer human interaction

Member, DGTF, Deutsche Gesellschaft für Designtheorie und -forschung, German society for design theory and research.

January 2015

List of publications

Articles in internationally reviewed journals

- Condotta, M., Nagel, T., and Stefanelli, C. Browsing and Correlating Architectural and Territorial Data in Tangible Maps: New Knowledge Opportunities in New Learning Places. Interaction Design and Architecture Journal (IxD&A) 9-10 (2010), pp. 49–62.

Papers at international conferences and symposia, published in full in proceedings.

- Nagel, T., Maitan, M., Duval, E., Vande Moere, A., Klerkx, J., Kloeckl, K., and Ratti, C. Touching Transport – A Case Study on Visualizing Metropolitan Public Transit on Interactive Tabletops. In Proceedings of the International Working Conference on Advanced Visual Interfaces (2014), AVI '14, ACM, pp. 281–288.
- Anwar, A., Nagel, T., and Ratti, C. Traffic Origins: A Simple Visualization Technique to Support Traffic Incident Analysis. In Proceedings of the Pacific Visualization Symposium (2014), PacificVis '14, IEEE, pp. 316–319.
- Nagel, T., Klerkx, J., Vande Moere, A., and Duval, E. Unfolding — A Library for Interactive Maps. In Proceedings of the International Conference on Human Factors in Computing and Informatics (SouthCHI), A. Holzinger, M. Ziefle, M. Hitz, and M. Debevc, Eds., vol. 7946 of Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2013, pp. 497–513.
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